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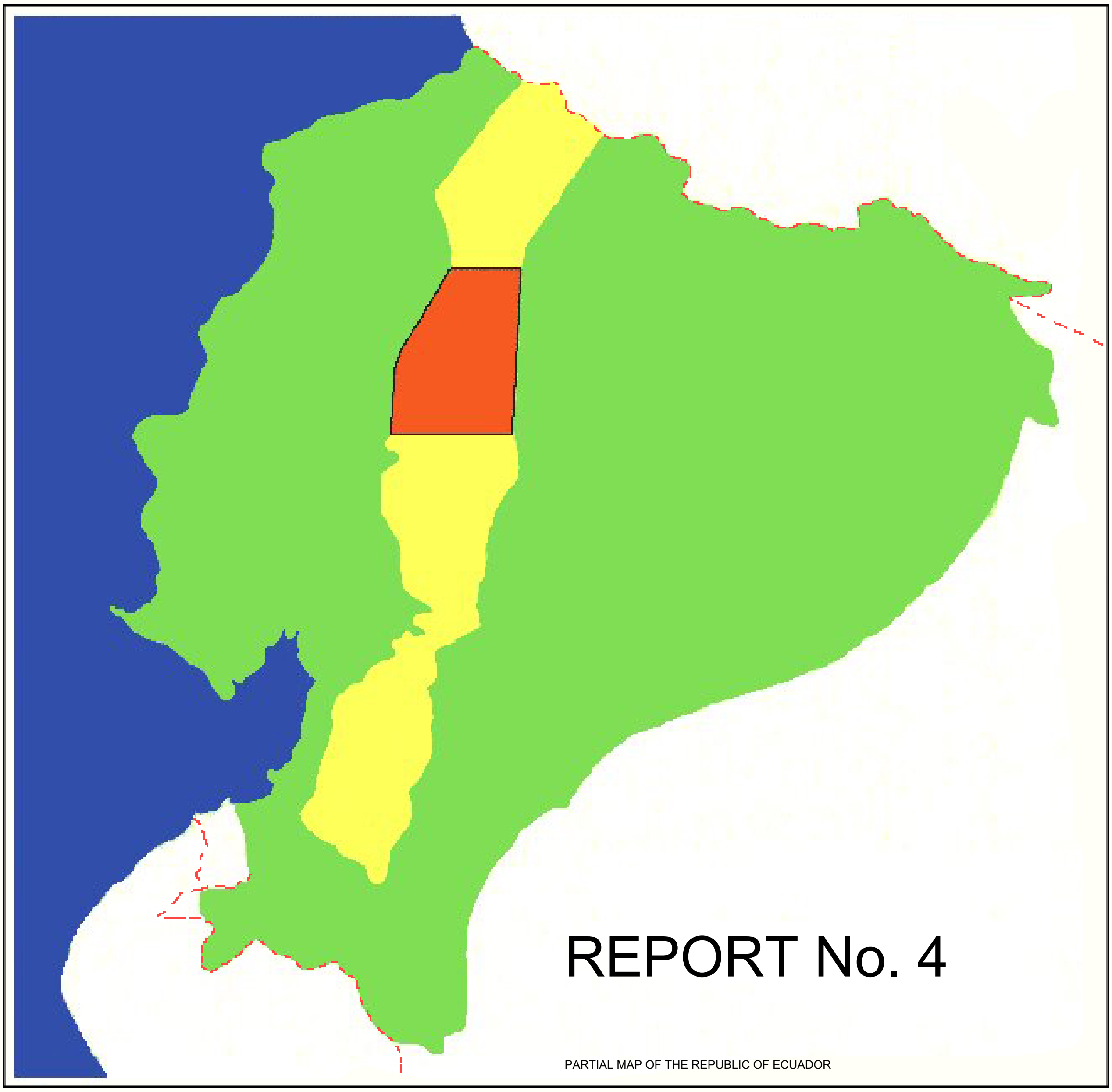

PARTIAL MAP OF THE REPUBLIC OF ECUADOR

WORLD BANK MINING DEVELOPMENT AND ENVIRONMENTAL CONTROL PROJECT

GEOLOGICAL INFORMATION MAPPING PROGRAMME (WESTERN CORDILLERA)

PATRI MATRIQUE

MINING DEVELOPMENT AND ENVIRONMENTAL CONTROL PROJECT

GEOLOGICAL INFORMATION MAPPING PROGRAMME

Report Number 4

GEOLOGY OF THE WESTERN CORDILLERA OF ECUADOR BETWEEN 0°00’ AND 1°00’S

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CODIGEM-BRITISH GEOLOGICAL SURVEY

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1. INTRODUCTION

This report describes the lithostratigraphy, structure and known mineralisation of the *Cordillera Occidental* (Western Cordillera) of the Ecuadorian Andes between 0°00' and 1°00'S and is an accompaniment to the 1:200000 scale geological map of that area, due to be published in 1999. Geological reconnaissance mapping of this quadrangle, at a scale of 1:50000, was carried out as part of sub-component 3.3., the Geological Information Mapping Programme (GIMP), of the *Proyecto de Desarrollo Minero y Control Ambiental* (PRODEMINCA) (Mining Development and Environmental Control Technical Assistance Project). This multi-national project is co-funded by the World Bank and the Governments of Ecuador, Sweden and the United Kingdom (formerly the Overseas Development Administration, ODA, now Department for International Development, DFID). One of its primary objectives is to attract private investment into the Ecuadorian mining sector, through the production of a comprehensive geological and geochemical database for the Western Cordillera. Geological investigations were undertaken jointly by geologists of the British Geological Survey (BGS) the Corporación de Desarrollo e Investigación Geológico-Minero-Metalúrgica (CODIGEM) and national consultants of PRODEMINCA.

The information and interpretations presented in this report are the product of approximately 180 days spent in the field between September 1995 and January 1996, and May to November 1996. The mapping team consisted of Dr. Richard Hughes (BGS), Ing. Ramiro Bermúdez (PRODEMINCA), Ing. Gavino Espinel (CODIGEM; up to June 1996), and Ing. Jorge Roldán (CODIGEM; present during the field trip of September 1996). Access to much of the area particularly the eastern half, is relatively good. Areas with very poor access, mainly the west and north central parts, were reached on foot. A 20 km stretch of the Río Mulaute in the north was navigated for three days using a *balsa* raft.

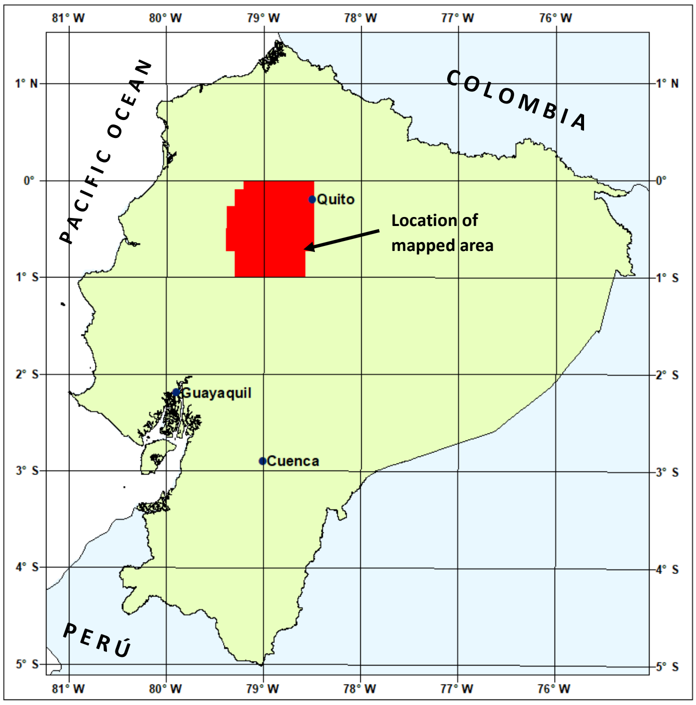

Figure 1. Location of study area

The location of the area within Ecuador is shown in Figure 1. Its approximate eastern limit is the generally concealed regional fault structure which separates the Cretaceous and Tertiary sequences of the Western Cordillera from the thick Quaternary volcanic deposits of the inter-Andean graben. Its western limit is the topographical break of slope which marks the contact between the Cretaceous and Tertiary sequences of the Western Cordillera and the flat, Quaternary terrace deposits of the coastal plain. Terrain and climate are remarkably varied. The lowest parts are in the west and lie between 200-250 m above sea level; these areas are intensively farmed, with bananas, cocoa, coffee, rubber and balsa the main export crops. The western slopes of the Cordillera rise very steeply to between 2500-3500 m and large parts of the area lie at these altitudes. These western slopes are generally covered by primary tropical forest, with very few settlements, poor access and a very wet and humid climate. Much of the south-east of the area lies above 4000 m; these areas consist of cold, inhospitable páramo populated by indigenous communities. The highest parts of the area are the Quaternary volcanic centres which line the eastern margin of the cordillera, part of Whymper’s (1892) famous ‘avenue of the volcanoes’. Of the six Quaternary volcanic centres along the eastern margin of the area, five exceed 4400 m and the glaciated peak Illiniza Sur is the highest at 5248 m.

2. GEOLOGICAL SETTING OF ECUADOR

2.1 Present day tectonic setting

The Andes form a continuous mountain range more than 7000 km along the active Pacific margin of South America, bounded to the west by an oceanic trench which extends from Patagonia to Colombia. The Andean range as a whole can be conveniently divided into three segments, namely the Southern, Central and Northern Andes (Gansser, 1973; Sillitoe, 1974). The Western Cordillera of Ecuador forms part of the Northern Andes segment, characterised generally by the presence of allochthonous terranes, including ophiolitic/oceanic fragments (Feininger and Bristow, 1980; McCourt et al., 1984; Megard and Lebrat, 1987) accreted to the margin of South America since the Mid Cretaceous (Egüez, 1986; Van Thournout, 1991). In broad terms, essentially orthogonal subduction of the Nazca Plate beneath continental South America is occurring in the Ecuadorian portion of this active margin at the present day. In detail, young oceanic crust (<20 Ma) produced by the Nazca-Cocos spreading centre at the Galápagos Rift Zone is being subducted in the Ecuadorian trench at an angle of 25-35° (Rea and Malfait, 1974; Lonsdale, 1978).

2.2 Regional geological context

Geographically and geomorphologically Ecuador can be divided into three main regions which reflect fundamentally different geological provinces. The Andean region or ‘Sierra’, separates the Amazon Basin or ‘Oriente’ in the east from the coastal plain or ‘Costa’ to the west. The Oriente is a Mesozoic to Cenozoic sedimentary basin which includes a platform carbonate sequence, overlying an older cratonic basement. Basement and cover sequences are both intruded by large granitoid batholiths, mainly along the complex sub-Andean zone of folding and thrusting that lies along the boundary between Oriente and Sierra.

The Sierra comprises two sub-parallel mountain chains separated by a central graben. The Cordillera Real to the east is dominated by linear belts of metamorphic rocks, intruded by Early Mesozoic granitoids of both S- and I-type, capped along much of its length by Cenozoic volcanics. The Western Cordillera to the west of the graben is dominated by Late Mesozoic to Early Cenozoic basaltic volcanic and volcanoclastic rocks (representing, at least in part, accreted oceanic terranes) and clastic turbidites, intruded by Mid to Late Tertiary granitoids and overlain by post-Eocene continental margin, mainly acid to intermediate, calc-alkaline volcanic sequences. The inter-Andean graben is an extensional structure bounded by active faults. It contains thick and extensive Tertiary to recent volcanosedimentary and volcanic sequences that probably date back to Oligocene-Miocene time. The Costa comprises the low-lying region west of the Andes and represents a Late Cretaceous to Cenozoic fore-arc basin, or series of basins underlain by basic oceanic crust exposed in the hills of the coastal cordilleras.

2.3 Summary of previous geological work in Ecuador

Wolf (1892) produced the first map and comprehensive geological and geographical synthesis of Ecuador. This remained the standard reference work until that of Sauer (1957, 1965), which included and complemented the earlier works by Tschopp (1948, 1953), based mainly on extensive but confidential studies of the sedimentary basins of Ecuador for the oil industry. Further systematic studies of the sedimentary basins were carried out by the French Petroleum Institute (*e.g.* Faucher et al., 1968), leading to the publication of a 1:1000000 scale national geological map in 1969 and the first geodynamic synthesis by Faucher and Savoyat (1973). During the period 1969-1980 a systematic mapping programme was carried out by geologists of the *Dirección General de Geología y Minas* (DGGM) and the Institute of Geological Sciences (IGS) (now the British Geological Survey), under a bilateral Technical Cooperation Project between the Governments of Ecuador and the United Kingdom. This work resulted in the publication of various 1:100000 regional geological maps and a new 1:1000000 national map and explanatory bulletin (Baldock and Longo, 1982; Baldock, 1982). Related publications on the geology and stratigraphy of Ecuador were those of Kennerley (1980), Bristow and Hoffstetter (1977), Bristow (1981) and Henderson (1979). Further, albeit more specialised regional studies include Sigal (1968), Goossens (1972), Goossens and Rose (1973), Feininger (1977, 1978) and DGGM (1980).

A second BGS-DGGM/INEMIN/CODIGEM technical cooperation project from 1986-1993 produced detailed reports and maps of the geology and mineral potential of the metamorphic basement of the Cordillera Real and El Oro area (Litherland et al., 1994; Aspden et al., 1995), a new 1:1000000 scale national geological map, and an accompanying tectono-metallogenic map (Litherland et al., 1993a, 1993b). The latter authors incorporated data from numerous sources in their National Geological Map of Ecuador, including university theses, reports of international missions to Ecuador (Misión Belga, Misión Francesa, Misión Japonesa) and studies by governmental institutions such as INEMIN/CODIGEM and INECEL.

2.4 Summary of previous research in the Western Cordillera

Ever since the earliest studies of Wolf (1892) it has been recognised that the main rock types of the Western Cordillera and Coastal Range are '*rocas porfídicas y rocas verdes*'. Tschopp (1948) was the first to introduce formal stratigraphic names for these sequences with the introduction of the term 'Piñón Formation' for the basic volcanic sequences of the Costa, while retaining Wolf's descriptive term for the basic volcanics of the Sierra. Sauer (1965) followed Tschopp in using the name Piñón Formation for the basic rocks of the Costa, and resurrected the term 'Cayo Formation' (*cf.* Olsson, 1942), for the overlying Late Cretaceous, marine, volcanosedimentary sequence. For the basic rocks of the Cordillera, he used the term 'Formación Diabásica-Porfirítica'. Sauer also used the term 'Yunguilla Formation', introduced originally by Thalmann (1946) for a sequence of marine turbidites of mainly Maastrichtian age from the Quito-Nono-Nanegal area of the Western Cordillera.

Systematic mapping by geologists of the Institut Français du Pétrole in the mid-sixties led to the first correlations between the Costa and the Western Cordillera. The name Piñón Formation was used for the Cretaceous oceanic basement comprising diabases and '*rocas verdes*'. The name Cayo Formation was retained for the overlying volcano-sedimentary sequence on the coast and the term 'Cayo de la Sierra' was introduced for its chronostratigraphic correlation in the Cordillera. Two further Formations were described: the previously mentioned Yunguilla Formation of Maastrichtian to Palaeocene age (confirmed by micropalaeontological studies in the Nono area northwest of Quito; Sigal, 1968), and a conformably overlying sequence of volcanoclastic conglomerates, sandstones, greywackes and green-purple shales of reputed Paleocene age, the 'Cayo Rumi Formation'. Goossens and Rose (1973) meanwhile proposed that both the Piñón and Diabase Porphyry Formations be renamed the Basic Igneous Complex and suggested a correlation with similar rocks from Costa Rica, Panama and Western Colombia on petrographic grounds.

Subsequent evolution of the stratigraphy of the Western Cordillera was influenced by the mapping of the IGS/DGGM geologists, in particular the tectono-stratigraphic interpretation of Henderson (1979) who proposed that the basic volcanics of the Cordillera and the Costa were different both in age and origin. In the early maps both 'Formación Piñón' and/or 'Complejo Ígneo' were used for the Costa rocks and 'Formación Piñón' in the Sierra. From 1976 onwards, however, new names were introduced following an interpretation of the oceanic volcanics of the Western Cordillera as an island arc from a combination of lithological and geochemical evidence. The name Piñón was retained but restricted to the basaltic ocean floor volcanics of the Costa, while the name Macuchi Formation was created for the 'rocas verdes' of the Western Cordillera, consisting mainly of basaltic to andesitic rocks a high percentage of which had been reworked.

The Macuchi as defined by Henderson was interpreted to be predominantly sedimentary, comprising volcanoclastic sandstone and siltstone turbidites, with lesser amounts of breccia, tuff and lava. It included essentially all the volcanic and volcanoclastic 'rocas verdes' of the Western Cordillera. The 'overlying' Late Cretaceous sediments, formerly named 'Cayo de la Sierra', were also considered to be part of the Macuchi Formation and renamed the 'Chontal Member'. In addition, the conglomeratic Cayo Rumi Formation on the Alóag-Santo Domingo road was renamed the Silante Formation and interpreted to directly overlie the Macuchi volcanoclastics, but was itself 'overlain' by the Yunguilla Formation of proven Maastrichtian to Palaeocene age as noted above. On this evidence the Macuchi Formation was interpreted to be Late Cretaceous or older. Further south however, to the east of Quevedo-La Maná, Early Eocene fossils were reported from the Macuchi Formation, and andesitic sills within the sequence yielded Mid Eocene K-Ar ages. In addition, Eocene fossils were recorded from the overlying 'Yunguilla-type' flysch sequence. The Macuchi Formation and by inference the overlying flysch unit were therefore interpreted by Henderson to be strongly diachronous and were attributed a (Late) Cretaceous to Eocene age along the length of the cordillera.

Almost simultaneously with Henderson's re-interpretation, Kehrer and Van der Kaaden (1979) subdivided the 'Piñón de la Sierra' (or Macuchi) rocks of the Alóag-Santo Domingo road section into three units. The Toachi Unit was considered to be equivalent to the coastal Piñón Formation; the Pilatón Unit was equated with the 'Formación Cayo de la Sierra' (the Chontal Member of Henderson), and the third unit was the distinctive, probably younger, Tandapi Beds.

This nomenclature was resurrected by Egüez (1986) whose work in the central part of the Cordillera was fundamental to understanding and partly resolving the Macuchi-Yunguilla dilemma introduced by Henderson (1979, 1981). Egüez (1986) demonstrated the presence of two lithologically similar turbidite sequences of different ages, both of which had been previously mapped as a single unit, the Yunguilla Formation. The fine-grained turbidite sequence of the Quito-Nono area, the true Yunguilla Formation, was known to be of Late Cretaceous to Early Palaeocene age. In contrast, Egüez demonstrated that the sandy turbidite sequence which overlies the Unacota Limestone to the east of Quevedo, the Apagua Formation, was of Mid Eocene age or younger. Egüez’ recognition of two discrete turbidite sequences resolved much of the earlier confusion and obviated the need for diachronous Formations.

In addition, Egüez reinterpreted the Silante-Yunguilla contact, and reversed the relative age relations of the two units. According to Egüez the Silante overlies, and is in apparent conformable contact with, the Yunguilla Formation. The age of the Silante remains problematic and poorly understood, but it is clearly post-Maastrichtian because it overlies and contains reworked fossils from the Yunguilla Formation (Savoyat et al., 1970). Van Thournout (1991) preferred a Palaeocene age for the Silante due to its position above the Yunguilla and its unproven contact relationships with the Macuchi Formation. Baldock and Longo (1982) depicted the Silante overlying the Macuchi in normal contact.

Egüez (1986) restricted the term Macuchi (*sensu stricto*) to a volcanic-volcanosedimentary unit of Early to Mid Eocene age, and also recognised the presence of oceanic floor basalts in the Western Cordillera. He suggested the name Toachi Unit for these and equated them with the Piñón Formation of the Costa. For the associated siliceous sediments, the former Cayo de la Sierra, he proposed the name Pilatón Unit (followed in this report). In contrast, Santos and Ramírez (1986), although in broad agreement with Egüez over the stratigraphic succession, proposed a reintroduction of the old stratigraphic nomenclature ‘Piñón de la Sierra’ and ‘Cayo de la Sierra’ for the basement sequences.

At about the same time Lebrat (1985), on geochemical grounds, showed that the Macuchi Formation of Henderson was made up of three distinct types of ‘basalts’: tholeiitic island-arc basalts, oceanic MORB and calc-alkaline arc basalts. The MORB rocks were correlated with the coastal Piñón Formation and the calc-alkaline volcanics mistakenly correlated with the Cretaceous Celica Formation of southern Ecuador (in fact they are part of the Oligocene Saraguro volcanics). According to Lebrat’s work, island-arc volcanics define the type Macuchi of the Western Cordillera. Similarly, Van Thournout et al. (1992) recognised the presence of three major volcanic sequences in the north-western part of the cordillera, an Early Cretaceous sequence of MORB basalts and overlying arc tholeiites, a mainly Eocene sequence of island-arc, tholeiitic to calc-alkaline, basalts and a (Mid to) Late Oligocene sequence of calc-alkaline volcanics of dominantly andesitic-dacitic composition. The first and second sequences correlate with the ‘Piñón/Toachi’ and Macuchi Formations respectively of Egüez (1986) and Lebrat (1985).

Finally, Litherland et al. (1993a) on the 1:1000000 National Map of Ecuador, divided the pre-Oligocene volcanics of the Western Cordillera into a Palaeocene to Eocene island-arc sequence (the Macuchi Unit) and a pre-Senonian ophiolitic (MORB) sequence, for which they used the name 'Piñón de la Sierra'.

In addition to the ensimatic volcanics of the Piñón and Macuchi Formations, at least four other calc-alkaline, continental-margin volcanic arcs are recognised in the cordillera; the Late Cretaceous Celica Formation of Southern Ecuador, an Oligocene to earliest Miocene sequence typified by the Saraguro Group andesitic to rhyolitic pyroclastic deposits, the Miocene volcanics and volcanoclastics of the Pisayambo Volcanics and regional equivalents, and the Plio-Pleistocene to Recent sequences that locally extend into the intermontane graben, for example the Turi and Sicalpa Formations (Baldock, 1982; Litherland et al., 1993a). All of these volcanic sequences are in general poorly defined and dated, and accordingly may contain the volcanic products of more than one phase of activity as presently mapped.

3. LITHOSTRATIGRAPHY

3.1 Stratigraphic summary

A regional fault structure with a history of dextral shear, the Toachi-Toacazo Fault, divides two different sequences within the present area (see Table 1). This structure is believed to be a terrane boundary, and is described in detail in section 5.1. South-west of the Toachi-Toacazo Fault, the rocks consist of Early Eocene (and possibly Late Palaeocene), mainly basaltic to basaltic andesite ocean floor volcanics and volcanoclastic turbidites of the Macuchi Unit, overlain by a clastic marine sequence of Paleocene to Eocene age, the Angamarca Group. These are intruded by Oligocene to Miocene, I-type, granitoid plutons and in part overlain by Oligocene, Miocene and Pliocene, acid to intermediate calc-alkaline volcanic and volcanoclastic sequences, capped by Quaternary stratovolcanoes. North-east of the Toachi-Toacazo Fault are marine volcanoclastic turbidite sequences of probable Senonian to Maastrichtian age, and a thick continental sequence of post-Maastrichtian age.

Table 1. Stratigraphical relationships of major sedimentary units about the Toachi-Toacazo Fault

NE of Toachi-Toacazo fault		SW of Toachi-Toacazo Fault	
	Silante Unit		Zumbagua Group
Non-sequence?		Unconformity	
	Yunguilla Unit		
Fault			Angamarca Group
	Pilatón Unit	Fault	
Fault			
	Mulaute Unit		Macuchi Unit

The age, distribution, facies, depositional environments and other salient features of these and other, non-sedimentary, lithostratigraphical units are described below. The units are described in approximate ascending stratigraphical order.

3.2 Pujilí Unit (K?$_{Pj}$)

3.2.1 Distribution

The Pujilí Unit (‘Pujilí ophiolite’ of Litherland et al., 1994) is a tectonic mélange containing a highly varied clast population. It is present only in the extreme south-east of the area between Pujilí and Saquisilí, where it is exposed along road sections and in a number of quebradas which drain eastwards from the watershed of the Western Cordillera into the inter-Andean graben. The best exposures are in Quebrada Maca Grande [754-9803], Quebrada Pusuchisi [755-9807], and Quebrada Picisi [755-9898]; in the latter there are spectacular, almost continuous exposures for a distance of at least 1 km. Outcrop patterns suggest that the Pujilí Unit is present in two, fault-bounded areas, separated by a slice of the Saquisilí Unit (see section 3.10).

The presence of the mélange at the surface in the Pujilí area is probably related to the existence of regional (active) faults here (see section 5.1), and it is possible that it underlies other parts of the cordillera along its margin with the inter-Andean graben. The cordierite-bearing metamorphic clasts reported by Bruet (1987) as xenoliths within extrusive rocks from Pichincha volcano may reflect the presence of the mélange at depth beneath Pichincha.

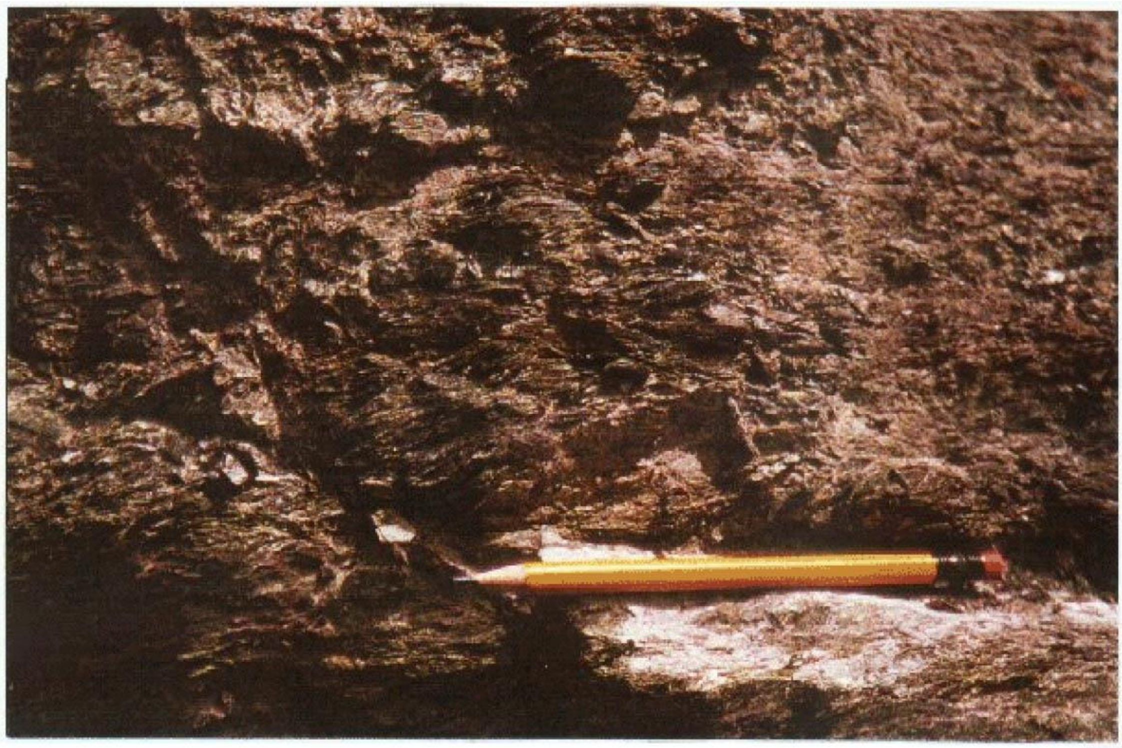

Plate 1a. S-C fabrics showing dextral movement in phyllites; see especially the area immediately above the pencil-tip. Pujilí Unit, Quebrada Pusuchisi [7550-98072]

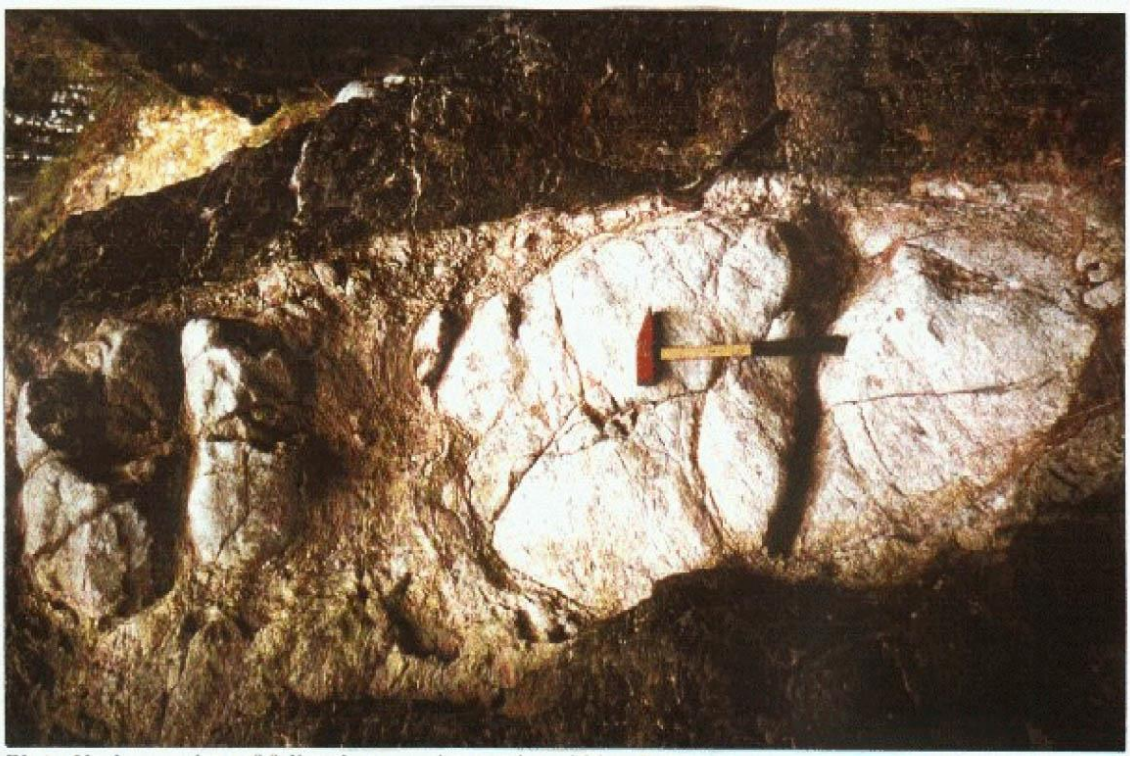

Plate 1b. Large clast of foliated muscovite granite within ultrabasic matrix. Pujilí Unit, Quebrada Picisi [7556-98986]

3.2.2 Age

The ages of the deformation event(s) within the mélange, and of the clasts within the unit, are unknown, but a Maastrichtian age for the deformation is suggested from regional considerations (see section 8). Samples of a red siliceous mudstone (which resembles a radiolarian ooze) and a cream-coloured, bioturbated mudstone (see below) were analysed for microfossils, but proved to be barren.

3.2.3 Lithologies

The Pujilí Unit is a totally chaotic and highly deformed tectonic mélange, with abundant evidence of high strain in the form of penetrative cleavage fabrics and crenulations in the matrix. Evidence of ductile deformation can be seen in Quebrada Picisi [7556-98986] and Quebrada Pusuchisi [7550-98072] (Plate 1a), where S-C fabrics indicate dextral movement towards approximately 065°.

Clast types include foliated serpentinised ultrabasic material containing chromite and magnesite, foliated muscovite-rich granitoids (similar to the Triassic (?) Tres Lagunas granites of the Cordillera Real; Ing. Pablo Duque, pers. comm.), amphibolites with L-tectonite fabrics (similar to the Triassic (?) Piedras Unit of the El Oro complex; Ing. Pablo Duque, pers. comm.), phyllites, possible basaltic pillow lavas, highly siliceous red siltstone/mudstone, and intensely bioturbated, cream-coloured mudstones. Many of these rock types are not known to occur elsewhere in the Western Cordillera, and the bioturbated, cream-coloured mudstones are unknown from elsewhere in the Andean region of Ecuador (J. Aspden, T. Feininger, pers. comms.).

Clasts are up to several metres in size, and are chaotically distributed throughout, but some clast types are more abundant in some areas than in others. For example, the highly siliceous red siltstone/mudstone is the most common clast type in Quebrada Pusuchisi, but is not present in Quebrada Picisi. A possible pillow lava sequence, believed to be part of the mélange, is present along a road section between Milipungo [7529-98042] and Comuna Tamborurcu [7538-98055], but spheroidal weathering of the sequence makes its interpretation difficult. In the Quebrada Picisi, a clast of ultrabasic material several metres across contains large (>2 m in size) ‘xenoliths’ of ‘Tres Lagunas’ type foliated granitoid (plate 1b).

3.2.4 Interpretation

The various lithologies present within the unit – pillow lavas, red siliceous siltstones, ultrabasics – are collectively representative of an oceanic suite, but also present are foliated granitoids and ultrabasics of non-oceanic affinities. It is difficult to envisage the Formation of this assemblage by anything other than tectonic processes. The mélange may represent part of a tectonic accretionary complex developed in a convergence (fore-arc) zone at the time of accretion of the Pallatanga (=Piñón) oceanic ‘terrane’ to the South American continental plate, at some time during the late Cretaceous (see section 3.4).

3.3 San Juan Peridotites ($K?_{Sj}$)

This sequence of basic and ultrabasic rocks is well known from the literature, and has been described as the 'ophiolitic assemblage of San Juan' by Juteau et al. (1977), as part of the Macuchi Unit by Henderson (1979), as a tectonic slice related to the Macuchi Unit by Cerezo et al. (1979) as an ophiolitic suite overthrust along a major basement fault by Lebrat et al. (1985), as the MORB affinity 'basic and ultrabasic complex of San Juan' by Egüez (1986), as a dismembered ophiolite within the Macuchi by Lebrat et al. (1987), and as the 'Saloya Ultramafic Complex' of ophiolitic affinity by Van Thournout (1991). The age of the unit is unknown, but most of the above authors suggest Cretaceous.

The San Juan Peridotites are in faulted contact to the east with Maastrichtian sediments of the Yunguilla Unit. To the west they are in probable faulted contact with MORB affinity basaltic intrusives and sediments of the Pallatanga Unit. The rocks of the Pallatanga Unit at San Juan were stated by Egüez (1986) to be geochemically similar to the MORB San Agustín Unit, exposed some 16 km south-southeast of San Juan along the Alóag-Santo Domingo road.

The best exposures of the San Juan Peridotites are along the Quito-Chiriboga road section at San Juan between [7610-99675] and [7587-99683]. Cerezo et al. (1979) and Van Thournout (1991) carried out detailed petrographical studies along the road section, and the reader is referred to these articles for further information. Ultramafic rocks, including serpentinised peridotites, are present at the western end of the section [7587-99683], with dolerites, anorthosites and gabbros (the latter containing ultramafic with possible cumulate textures) at the eastern end [7610-99675]. Similar rock types are exposed in the nearby Río Saloya.

The ultramafic-mafic assemblage of the San Juan Peridotites is clearly representative of a mantle sequence. Though the exact nature of the contact between the San Jan Peridotites and the Pallatanga Unit immediately to the west is unknown, the MORB affinities of the basaltic rocks of the Pallatanga Unit in the San Juan area (Egüez, 1986; Van Thournout, 1991) refute their association with the Macuchi Unit, which is known to be of non-MORB type (see section 3.9.6). The interpretation of the San Juan Peridotites and the Pallatanga Unit as fragments of a dismembered ophiolite (Lebrat et al., 1987) therefore seems likely.

3.4 Pallatanga Unit (K_{Pa})

Rocks of the Pallatanga Unit are present in four parts of the area, each in fault-bounded slices on the eastern side of the cordillera. Exposures are present along the Alóag-Santo Domingo road, along the Quito-Chiriboga road, along the Calacalí-Nanegalito road, and at Guayrapungu. The age of the Pallatanga Unit is unproven, but the sequence is believed to have been accreted in Late Cretaceous times, and is therefore interpreted to be of Late Cretaceous age. All available geochemical data suggests that the unit is of MORB affinity, and therefore represents fragments of oceanic crust now exhumed along the major north-south trending fault system which marks the eastern limit of the Western Cordillera.

The Pallatanga Unit is exposed along the Alóag-Santo Domingo road [7618-99506] some 7 km west-northwest of Alóag. This single exposure was named the San Agustín Unit by Egüez (1986), and stated to be of MORB-type. It consists of a single exposure of massive, intensely jointed, non-vesicular dolerites and basalts, which forms an inlier within modern andesitic lavas of Cerro Corazón. Pillows are absent, and it is not known whether the rocks are intrusive or extrusive. The regional contacts of the Pallatanga Unit with the Silante Unit to the west and (probably) with the Yunguilla Unit to the east are not exposed, but are inferred to be faulted.

Some 16 km north-northwest of the Alóag-Santo Domingo road, the Pallatanga Unit is exposed along the Quito-Chiriboga road, in the area of Finca Salvador [7575-99690]. The probably faulted eastern contact of the Pallatanga Unit here is with the ultramafic rocks of the San Juan Peridotites. The Pallatanga Unit is poorly exposed here, but consists of fine-grained, strongly vesicular, feldspar- and pyroxene-phyric, basaltic ?lavas, with related volcanoclastic sandstones containing clasts of vesicular basalt. The rocks of the Pallatanga Unit from this section were stated by Egüez (1986) and by Van Thournout (1991) to be geochemically similar to the MORB basalts of the San Agustín Unit, exposed along the Alóag-Santo Domingo road (see above).

A fault-bounded slice of Pallatanga Unit rocks is present within the Yunguilla Unit in the extreme north-east of the area. The best exposures are some 2 km north of 0°00', along the Calacalí-Nanegalito highway at [7705-00010], where a sequence up to 500 m of fine-grained, vesicular, possibly olivine-bearing pillow basalts are present. 3.5 km south of the road section at Cerro Pucará [7703-99977] are exposures of basaltic hyaloclastites and matrix-supported breccio/conglomerates containing vesicular basalt clasts, interpreted to be part of the same sequence of pillow lavas and related sediments. There is no geochemical data from this area.

Very deeply weathered and sheared basic igneous rocks are exposed as an inlier within the Zumbagua Group in the vicinity of the pueblo of Guayrapungu [742-9902], some 2 km north of the Zumbagua-Pujilí road. These rocks are interpreted to belong to the Pallatanga Unit, excised along a north-south trending regional fault.

3.5 Pilatón Unit (K_{Pl})

3.5.1 Distribution

Formerly known as the 'Formación Cayo de la Sierra' (Servicio Nacional de Geología y Minería, 1969), it is here named the Pilatón Unit following Egüez (1986) and Van Thournout (1991). Within the present area it exists only on the north-eastern side of the Toachi-Toacazo Fault. Its eastern contact with the Silante Unit is a fault, and its western contact, also probably faulted, is with the Mulaute Unit. Locally, along the Santo Domingo road, its western contact is probably with the La Esperie quartz diorite intrusion. Neither contact was exposed at the time of this survey, though Egüez (1986) suggested that the western contact (with the supposedly underlying Cretaceous volcanosedimentary Toachi Unit, see Egüez, op. cit.) is concordant. Van Thournout (1991) mentioned a 'conformable and gradual transition' with the Toachi Unit, but gave no locality details.

The best exposures of the Pilatón Unit are along the Alóag-Santo Domingo road, where a thickness of up to 4000 m may be present. Further exposures are present along the old Quito-Santo Domingo road west of Chiriboga and in the valleys of the ríos Cinto and Saloya west of Mindo. Lithologies typical of the unit have been identified in floats in Estero La Sucia south-east of San Miguel de los Bancos, and in the Río Cocaniguas between San Miguel de los Bancos and Puerto Nuevo.

3.5.2 Age

A Senonian (Late Cretaceous) age for the Pilatón Unit is indicated by the foraminifera *Globotruncana* sp., *Guembelina* sp., and *Globigerina* sp. (Sigal, 1968) and by the ammonite *Inoceramus peruanus* (Faucher and Savoyat, 1973 – all specimens collected from the Alóag-Santo Domingo road section; see Bristow and Hoffstetter, 1977, for further details). It was this evidence that led to the correlation of the Sierra sequence with the Formación Cayo of the Costa, and the coining of the term 'Cayo de la Sierra'. However, despite their apparent contemporaneity, the use of the term 'Cayo' for the two sequences is an oversimplification of a complex situation, and the term 'Pilatón Unit' is preferred here.

3.5.3 Facies

The sequence observed during the present study is entirely sedimentary, though Van Thournout (1991) reported the presence of 'intercalations of basaltic pillow lavas', again regrettably from unspecified localities. The sequence along the Alóag-Santo Domingo road (between [7438-99567] and [7389-99617]) consists of commonly pale-green, thin- to thick-bedded, medium- to coarse-grained turbidite sandstones, with some very coarse breccia beds, in Bouma $T_{abcd(e)}$ sequences. Grading, loading, sole structures, and cyclic Bouma sequences indicate a consistent south-east younging direction along the road section, with some minor folding seen at, for example [7395-99618]. The best and freshest exposures are in a recently blasted road-cut at [7412-99599]. Some units here are up to 3 m thick and may be amalgamated turbidite flows. $T_{c\&d}$ units are commonly intensely bioturbated (*Chondrites* type mottling). The rocks are generally well-sorted, crystal-lithic sandstones, but poorly-sorted, coarse-grained sandstones and breccias are present. Plagioclase is abundant, quartz is common, and pyroxene is present but uncommon. Amphiboles and other mafics have not been seen. Lithic clasts are common, and are almost exclusively of fine-grained, basic to intermediate, igneous material (thin-sections RH-136, RH-137, RH-138a-f). Highly vesicular (with chlorite infills), fine-grained, basaltic to andesitic lithoclasts are extremely common, and constitute as much as 30% of some rocks (e.g. thin-section RH-138c). Sedimentary lithoclasts of fine-grained, quartz sandstone are present but rare. The sequence is secondarily silicified and chloritised throughout, with some epidotisation; the origin of these characteristics is unknown but low-grade, ocean floor metamorphism is a possible cause.

North of the Alóag-Santo Domingo road the Pilatón Unit is exposed along the Quito-Chiriboga road between Hacienda Las Palmeras [7451-99727] and El Tránsito [7385-99669]. These exposures are generally small and intensely weathered; the best are in the vicinity of El Carmen [742-9971], where thin- to medium-bedded, grey-green siltstones and fine-grained sandstones are present. Better exposures are present on the right banks of the Río Saloya [7428-99978] and Río Cinto [7433-99965], where sequences of pale green, silicified and chloritised, matrix-supported breccias and coarse-grained, poorly sorted sandstones are present. The breccias contain abundant clasts of highly vesicular andesitic material and possible black cherts. The sandstones are very similar to those described above from the Alóag-Santo Domingo road section; they are of crystal-lithic composition, with plagioclase, quartz and abundant pyroxene, and lithoclasts of vesicular andesitic material (RH-323, RH-324b).

3.5.4 Depositional environment and provenance

The turbidite facies of the Pilatón Unit are typical of proximal to medial position on a submarine turbidite fan. The overall composition of the sandstones indicates a basic to intermediate volcanic source. The abundance of highly vesicular lithoclastic material of basaltic/andesitic composition is indicative of a basic to intermediate effusive volcanic source. The absence of primary tuffs, accretionary lapilli and other indicators of subaerial explosive volcanism within the sequence and the presence of marine fossils suggest that the volcanic source was submarine. Furthermore, because considerable submarine topography is required to facilitate the development of extensive submarine turbidite fans it is probable that the source of the material was a volcanic island-arc system rather than a marginal basin spreading centre.

3.6 Mulaute Unit (K?$_{Ml}$) (see also section 5.2)

3.6.1 Distribution

The Mulaute Unit is present only in the north-west of the area, on the north-eastern side of the Toachi-Toacazo Fault. It is generally very poorly exposed, being concealed beneath extensive Quaternary terrace deposits. The best exposures are in the valley of the Río Mulaute (from where the sequence takes its name) between the Cooperativa Mar de La Tranquilidad [733-9977] and the suspension bridge at Diez de Agosto [724-9985]. Further exposures are present in the valley of the ríos Macas [726-9992] and Cocaniguas [729-9988], and along the Alóag-Santo Domingo road and the adjacent Río Pilatón section between San Antonio [737-9963] and Loma La Palma [731-9964]. A few, very deeply weathered exposures are present along the old Chiriboga-Santo Domingo road between El Tránsito [738-9966] and Santa Isabel [731-9965].

The Mulaute is a new unit. The sections in the valleys of the ríos Mulaute, Macas and Cocaniguas are previously undescribed, and are the only exposures in an otherwise low-lying, densely forested area. For the most part the exposures in the Río Mulaute are accessible only by boat; during this study the excellent and unique type section (some 20 km along) between a point some 3 km east of Puerto Nuevo [7293-99799] and the bridge at [7186-99887] was surveyed using a balsa raft.

The western limit of the unit is the Toachi-Toacazo Fault, exposed in the Río Pilatón at [7314-99649]. The eastern contact is with the Pilatón Unit: this is also thought to be a fault, but is unexposed. The true thickness of the Mulaute Unit is therefore unknown and cannot be easily calculated because of the paucity of exposure and the lack of structural data for much of the area. However, it is clear that the thickness of the unit is measurable in thousands of metres.

3.6.2 Age

The age of the Mulaute Unit is unknown. However, because the Toachi-Toacazo Fault divides a sequence of Late Cretaceous-Early Tertiary age on the north-east side from a Mid-Paleocene and younger sequence on the south-west side (see section 5.1) it is speculated that, in common with its neighbours, the Mulaute Unit is of Late Cretaceous age.

3.6.3 Facies

The Mulaute Unit is a sedimentary sequence which comprises a variety of facies with variable volcanic input. Minor diabase intrusions are present but uncommon. The easternmost part of the sequence, exposed between the eastern (probably faulted) contact with the Pilatón Unit and a point [7278-99795] some 800 m east of Puerto Nuevo, is a volcanoclastic sandstone sequence. This is best exposed in the Río Mulaute, where it is intensely sheared in parts, and along the Alóag-Santo Domingo road and the adjacent Río Pilatón, where it is relatively undeformed.

The volcanosedimentary sequence along the Santo Domingo road is exposed at Finca San Carlos [7373-99633], where it consists of massive, weakly foliated, poorly sorted, fine-grained breccias, rich in plagioclase and containing fine-grained intermediate composition igneous clasts with K-feldspar (see thin-sections RH-248 a and b). West of here the volcanosedimentary sequence continues with massive, tuffaceous, fine-grained breccias containing igneous clasts of intermediate composition with K-feldspar, exposed for example at Las Cascadas del Toachi [7432-99633]. Between here and the Toachi-Toacazo Fault the sequence generally contains less volcanic input, and consists of thick-bedded, mafic-poor, quartz sandstones with some beds rich in volcanic material; this sedimentary packet has not been recognised along strike to the north in the Río Mulaute section.

The volcanosedimentary sequence is also exposed in the Río Mulaute between Cooperativa La Mar de La Tranquilidad and point [7278-99795]. At the eastern end of the section at La Mar de La Tranquilidad are massive, fine-grained, matrix-supported breccias containing lithoclasts of highly vesicular igneous material of intermediate composition, containing pyroxene and K-feldspar (thin sections RH-253 and 254). These rocks contain large, zoned pyroxenes seen elsewhere within the Mulaute Unit at Diez de Agosto (see below). Further west at [7293-99799] are highly sheared, massive, poorly sorted quartz-feldspathic sandstones containing detrital amphibole and lithoclasts of fine-grained, plagioclase-rich igneous material (thin-section RH-339). These rocks are chloritised and epidotised, with chlorite growth in strain shadows around grains and within ‘boudinaged’ grains. Similar deformed, epidotised, poorly sorted, coarse-grained quartz-lithic sandstones containing detrital amphibole (see thin-sections RH-335-338) are present between here and the point [7278-99795], where there is a fundamental change in rock type.

Between this point and the suspension bridge at Diez de Agosto [7224-99882], approximately 90% of the sequence consists of intensely cleaved, fine-grained, laminated dark-grey mudstones and siltstones, with occasional thin sandy beds. These rocks are well exposed at readily accessible localities beneath the bridges at Puerto Nuevo [7270-99796] (thin section RH-256) and Diez de Agosto, and at numerous localities in the Río Mulaute accessible only by boat. Their thickness is uncertain because of the lack of structural data, but it is of the order of several hundred metres.

Within this mudstone sequence are at least two intervals of massive, coarse, matrix-supported lithic breccias and sandstones, containing abundant clasts of vesicular andesitic material. At [7257-99818] is an approximate thickness of 200 m of poorly sorted, coarse-grained, crystal-lithic sandstones, containing plagioclase, pyroxene and common amphibole, and lithoclasts of highly vesicular, plagioclase-phyric andesite containing pyroxene (thin-section RH-340). At [7224-99882] are exposures of a substantial thickness of massive, unsorted, coarse-grained lithic-rich sandstones containing abundant, fresh, zoned, euhedral pyroxene megacrysts, and common detrital amphibole (thin-sections RH-341a, c); these sandstones contain fine-grained, amphibole-bearing, intermediate igneous clasts, and fine-grained, highly vesicular igneous material. These are the westernmost basement rocks exposed in the Río Mulaute.

Further exposures of the Mulaute Unit are present to the north of the Río Mulaute in the ríos Macas and Cocaniguas. In the Rio Macas is exposed the same mudstone-siltstone sequence as that described from the Río Mulaute. Medium- to thick-bedded, turbidite sandstones are present within this sequence at [7890-99261] (thin-section RH-325b) and [7270-99925], and are of quartz- lithic composition, with abundant mudstone lithoclasts and fine-grained, vesicular igneous material. (These localities are most remarkable for their ductile deformation and S-C fabrics, described separately in section 5.2 of this report). Further north along the Río Macas at [7279-99956] the mudstone-siltstone sequence is very well-exposed in a riverside quarry, where dark-grey, thin- to thick-bedded, internally laminated fine-grained turbidites with thin, ripple cross-laminated, sandy beds are present: these rocks have a penetrative slaty cleavage.

A sequence of medium- to thick-bedded hornfelsed sandstones of the Mulaute Unit is exposed in the Río Cocaniguas at [7296-99877]. The metamorphism here is thermal rather than dynamic (see thin-section RH-327), as demonstrated by the absence of intense tectonic fabrics, and is probably related to the intrusion of a diorite body (see section 4.3 for further discussion).

3.6.4 Depositional environment and source

Though parts of the Mulaute Unit are difficult to interpret because of their intense deformation, there can be no doubt that the sequence was deposited in a submarine turbidite fan environment. A wide range of depositional processes is represented, from mass flow in the case of massive, matrix-supported, lithic breccias, to mud-silt grade turbidite deposition in the case of the thick sequence of cleaved mudstones and siltstones present in the Puerto Nuevo area.

The abundance of highly vesicular igneous material clearly suggests an effusive source. This source may have been subaqueous, but the apparent absence of hyaloclastites, pillow lavas and other evidence of subaqueous effusive activity from the sequence does not support this interpretation. The source of the volcanic material within the sequence was clearly different from that of the adjacent Macuchi and Pilatón units. The main difference is in the common presence of amphibole and K-feldspar in matrix and lithic material throughout the Mulaute Unit sandstones and breccias, which clearly indicates a more acidic/calc-alkaline source than those of the Macuchi and Pilatón.

3.6.5 Comparison of the Mulaute and Pilatón units

Although there is a superficial similarity between the rocks of the Mulaute and Pilatón units, in detail the sequences are quite different and can be distinguished by the following characteristics. The Pilatón Unit consists predominantly of well-sorted material in regularly bedded turbidite units with commonly recognisable T_{abc} sequences; there is very little facies or compositional variation within the sequence. In contrast, the Mulaute Unit consists of a variety of sedimentary facies, from very poorly sorted sandstones and mass-flow breccias to mud-silt grade turbidites. Some have a high volcanic input, others very little, and lithoclastic material is relatively more abundant than in the Pilatón. The different sediment sources of the two units are demonstrated by the presence throughout most of the Mulaute Unit of amphibole and K-feldspar, both detrital and within lithoclasts. Though both units have undergone secondary chloritisation, within the Pilatón it is far more intense and extensive than within the Mulaute. Conversely, secondary epidotisation is common within the more volcanic-rich sequence of the Mulaute, but is absent from the Pilatón. The presence of shards within the Pilatón is probable evidence of submarine effusive activity; in contrast no similar evidence has been found within the Mulaute.

3.7 Yunguilla Unit (K_Y)

3.7.1 Distribution

The Yunguilla Unit consistently occupies a structural position at the eastern margin of the Western Cordillera Cenozoic sequence, immediately adjacent to the Pujilí-Calacalí Fault. The most important exposures are in the type area around Alambi [765-9993], between 2 and 5 km west of Nono along the Nono-Tandayapa road (see Thalmann, 1946; Bristow and Hoffstetter, 1977), where a thickness of at least 2000 m is present. The quality and quantity of exposure in the type area are generally poor, but they are adequate to characterise the unit with reasonable confidence. In addition, there are two isolated exposures south of the Pichincha massif; one west of Lloa and the other along the Quito-Chiriboga road.

The unfaulted contact between the Yunguilla and the Silante is well exposed [7684-99009] along the Calacalí-Nanegalito road. There may be a depositional hiatus at this contact. The scant way-up evidence at the contact, in particular the grading of sandstone beds within the Yunguilla, is inconclusive. However, an impressive loaded base to a Yunguilla sandstone bed within 100 m of the contact at [7685-00009], and a weakly erosional base to a sandstone bed within 50 m of the contact in the Río Chiquilpe [7684-00008], both appear to indicate that the Yunguilla is older than the Silante Unit. The base to the Yunguilla Unit is not seen.

3.7.2 Age

The age of the Yunguilla Unit in the present area was determined by Savoyat et al. (1970) and by Faucher et al. (1971) as Danian (earliest Palaeocene), on the basis of foraminifera evidence from the Quebrada Alambi [766-9993] 4 km west of Nono. The faunal lists of these authors have been reassessed by Dr. Ian Wilkinson (BGS, Nottingham), who states that they indicate an age no younger than Maastrichtian. A Campanian to Maastrichtian age was also reported by Dr. Etienne Jaillard (Institut Dolomieu, Grenoble, France) in a personal communication (February, 1996) to Ing. Rommel Villagómez (formerly of the Misión Británica). It appears therefore, that there is no reliable evidence for a Palaeocene age, and that in its type area the Yunguilla Unit is of Maastrichtian age.

3.7.3 Facies

The typical lithologies in the type area are dark grey, massive siltstones and very fine-grained sandstones, in parts calcareous, with fissile siltstones and mudstones. Bedding is typically rhythmic, with thin to medium (10-20 cm) beds of massive siltstone and fine-grained sandstone alternating with thin (<5 cm) fissile siltstones and mudstones (T_{bde} units). Medium- to coarse-grained quartz arenites are present but uncommon; these occur in beds up to 40 cm thick, are poorly sorted, and are often graded (T_a units). Wavy and discontinuous bedding, and evidence of soft-sediment deformation are common. Grading and cyclicity of bedding are indicative of deposition from turbidite flows. Savoyat et al. (op. cit.) report bituminous beds.

Some 20 m of medium-bedded siltstones and very fine-grained sandstones are exposed beneath 'recent' lavas at [7629-99753], west of Lloa. A set of poor exposures at [7618-99675] between San Juan de Chillogallo and Chiriboga (along the Quito-Chiriboga road) consists of thin- to medium-bedded siltstones, and fine-grained sandstones with thin quartz arenite beds containing possible red siltstone clasts. These rocks are correlated with the Yunguilla Unit on the basis of lithological similarity.

The sandstones are well-sorted, but grains are always angular to sub-angular. Three thin sections from the type area (RH-163, 169, and 201) are quartz-feldspathic (plagioclase and rare microcline, sometimes zoned) sandstones, with very rare ferromagnesians (probably pyroxenes) now altered to chlorite/biotite/muscovite. Strained quartz aggregates indicate a metamorphic source, and RH-201 contains small grains of serpentinised amphibole. RH-169 contains rare but excellent shards, indicating contemporaneous volcanism.

3.7.4 Depositional environment

The Yunguilla Unit undoubtedly represents marine turbidite fan deposition. The generally fine grain size, the rarity of coarse-grained, graded T_a units, and the presence of carbonate-rich beds indicate deposition on distal fan lobes, away from a regular supply of coarse-grained clastic input.

3.8 Silante Unit (PcE_S)

3.8.1 Distribution

There are three principal sections through the Silante Unit in the area. The type area is along the Alóag-Santo Domingo road, and other sections are present along the old Quito-Santo Domingo road and the Nono-Tandayapa road. A fourth section through the unit, along the Calacalí-Nanegalito road, lies just a few kilometres to the north of the area.

3.8.2 Age

The age of the Silante is poorly established and problematic. Savoyat et al. (1970) state that the unit contains foraminifera derived from the supposedly underlying Yunguilla Unit, which itself is known to be of Maastrichtian age (see section 3.6.2). This interpretation would mean that the Silante is of post-Maastrichtian age. The unfaulted contact between the Silante and the underlying Yunguilla Unit is exposed along the Calacalí-Nanegalito road section. The nature of this stratigraphical relationship and the known Maastrichtian age of the Yunguilla also indicate a post-Maastrichtian age for the Silante Unit.

Wallrabe-Adams (1990) reports a K-Ar whole-rock age of 52.7 ± 2.9 Ma from 'quartz-latiandesite' lavas in the Silante Unit between Nono and Nanegalito. The presence of these lavas could not be confirmed during the present survey work, and the date is therefore regarded with some suspicion. An age of 16.8 ± 0.8 Ma (middle Miocene) was obtained by fission-track analysis of zircons from a sample (RH-188; from the Calacalí-Nanegalito road section at [7615-00029]) of monomictic, crystal- and lithic-rich tuffaceous sandstones and breccias, with abundant lithoclasts of probable andesitic lava material (Steinmann, 1997). The laboratory report indicated the highest possible level of confidence in this analysis. However, if the Wallrabe-Adams age of 52.7 ± 2.9 Ma is believed, the two dates imply continuous sedimentation during a period of at least 36 Ma, from early Eocene to middle Miocene times. Until further corroborative evidence is obtained the significance of these ages is unclear, and they are therefore regarded with some suspicion.

3.8.3 Facies

The type succession is exposed between the Quebrada Bomboli [757-9950] some 15 km west of Alóag, and the Quebrada La Plata [746-9952] some 2 km south-east of Tandapi. Exposures along the type section are not continuous, but are sufficient to characterise the succession with reasonable confidence. The Río Chisinche divides the succession into two, unequal parts. East of the Chisinche it consists of interbedded 'red beds' (siltstones and fine-grained sandstones), poorly sorted massive sandstones, and matrix-supported conglomerates. West of the Río Chisinche the sequence consists entirely of massive, matrix-supported breccias and conglomerates.

The sandstones which form much of the succession east of the Chisinche are thickly bedded (up to 1.5 m), generally massive, and coarse- to very coarse-grained. Compositionally they are lithic- and crystal-rich arenites, containing unstrained quartz, plagioclase, K-feldspars, pyroxenes and amphiboles. Grading has been seen only at one locality [7535-99515], but there is no other evidence of possible deposition from turbidity currents. The conglomerates within the same sequence are very thick bedded, massive and matrix-supported. The matrix of the conglomerates within the sequence is of similar composition to the sandstones. Clasts within the conglomerates are mostly of sedimentary rock types: black and red cherts, quartz pebbles, and red siltstones/sandstones (intraformational) are common, but clasts of fine-grained andesite are also present. The chert and quartz clasts are normally very well rounded, the intraformational clasts are commonly angular. In parts the succession is sandstone-dominated, but thicknesses of up to 20 m of red sandstones/siltstones are present. The red bed sequences are generally poorly exposed, but where seen they are thick-bedded and massive, with silica concretions in some beds. A sandstone channel, up to 1 m thick and some 20 m long, is visible within a red bed sequence at [7548-99519].

In contrast, the sequence west of the Río Chisinche in the type area consists of massive, totally unsorted, chaotic, matrix-supported breccias, with angular clasts of mainly igneous composition in a crystal-rich (plagioclase and pyroxene) matrix. Clasts consist mainly of feldspar phyric, andesitic intrusives, with less common, large, angular, intraformational red bed clasts. On the Machachi 1:100000 scale geological sheet, the sequence west of the Río Chisinche is interpreted as Macuchi Unit. There are, however, no similarities between this sequence and the type development of the Macuchi Unit (which consists of basaltic sheets and pillows, hyaloclastites and sandstones rich in vesicular basaltic material).

At the western end of the succession west of the Río Chisinche is a sequence of andesitic breccias (bA on the accompanying map), named by Kehrer and Van Der Kaaden (1979) the 'Tandapi Beds', and by Egüez (1986) and Van Thournout (1991) the Tandapi Unit. Kehrer and Van Der Kaaden (1979) and Egüez (1986) demonstrated the calc-alkaline nature of these andesites. Egüez believed the unit to be a sequence of andesitic lavas and breccias of Palaeocene age, in 'transitional' contact with the Silante Unit. Van Thournout doubted Egüez' interpretation of the contact relations along the Alóag-Santo Domingo road section, and instead interpreted the unit as a sequence of lavas and breccias of Upper Oligocene age.

The sequence is best exposed in a set of recent road cuts [746-9953] on the north side of the Río Pilatón at Tandapi, where it consists of massive, clast-supported breccias. Indeed, with the exception of small isolated exposures north and south of the valley of the Río Pilatón, these are the only extensive exposures of the sequence. Despite the claims of previous authors, the contacts of the unit are apparently not exposed. The clasts are almost exclusively of hornblende- and plagioclase-phyric andesites, though very rare intraformational mudstone clasts are also present. Andesite clasts are always highly angular, while the sedimentary intraformational clasts are rounded. The matrix consists exclusively of very fine-grained red mudstone and siltstone, and volumetrically constitutes a very small proportion (< ca. 2%) of the rock. At the microscopic scale minute clasts of andesite are commonly totally supported by this matrix, but at the outcrop scale the breccias are clast-supported. Andesite clasts with 'jigsaw fits' are commonly separated by narrow (up to 2 mm) 'veinlets' of red mudstone. It is difficult to explain the mobilization and deposition of breccias containing such a small proportion of matrix and an almost monomictic clast population by normal processes of mass-flow. However, the high clast to matrix ratio, the high degree of angularity of the andesite clasts, the intimate mixing of clasts and matrix, the presence of jigsaw fit clasts, and the almost monomictic clast population can be explained by explosive hydromagmatic reactions which would occur if a body of andesite was intruded into Silante Unit red mudstones containing interstitial water. The 'Tandapi Unit' is here interpreted as part of a Silante Unit red-bed sequence, intruded by high-level andesitic sheets. Dr. Arturo Egüez (pers. comm, April 1997) reports thin andesitic lavas interbedded with sediments in the nearby Quebrada Chorrera Negra [747-9950].

North of the type area, the Silante Unit is exposed along the Quito-Chiriboga road, but the degree and quality of exposure are poorer than those in the type area. The sequence appears to be similar in most respects, but two exposures demonstrate features of importance to the sedimentological interpretation of the unit. At [7553-99697] there is a sequence of poorly sorted, coarse-grained, micaceous sandstones, red-brown siltstones, and massive, unsorted, quartz-rich breccio-conglomerates. The lowest 20 cm of the breccio-conglomerate unit is cross-laminated, and contains three, thin, laterally continuous beds (up to 15 mm thick) of apparently pure magnetite. Magnetite-rich laminae are also present higher in the sequence here. The magnetite bands are interpreted as possible placer beds. One kilometre west of here at [7543-99696] are exposures of red siltstones and fine-grained sandstones containing amorphous carbonate nodules. These are probably pedogenic caliches.

North of the Pichincha massif the Silante Unit is exposed along the Nono-Tandayapa and Calacalí-Nanegalito roads. The exposures between Calacalí and Nanegalito are more continuous and fresher than those in the type area. Three components of the sequence can be mapped in both sections. At the contact with the Yunguilla Unit is a sequence of unsorted, chaotic, matrix-supported breccias and conglomerates consisting of mainly feldspar-phyric igneous clasts in a feldspathic sandy matrix. The middle component is a red bed sequence, consisting of red-brown siltstones, fine-grained sandstones and breccias, with probable pedogenic carbonate caliches at least at one horizon. The third component, which comprises most of the sequence, consists of typical Silante sandstones: they are mostly lithic-rich quartz arenites, and in parts contain abundant ferromagnesian minerals (pyroxenes and amphiboles) and magnetite-rich, probable placer horizons.

Within the sandstone-dominated unit along the Calacalí-Nanegalito road at [7645-99037] there is a 3 m sequence of yellow-buff coloured, parallel-laminated claystones containing well-preserved angiosperm leaves. These beds may be lacustrine, but clearly are of terrestrial origin. Along the same road at [7615-99029], tuffaceous sandstones containing flattened lithic clasts indicate contemporaneous, probably subaerial explosive volcanism.

3.8.4 Depositional environments and provenance

Several lines of evidence suggest that the Silante Unit was deposited in a non-marine, continental environment. Much of the succession, particularly in the north, consists of red beds, and such sequences are widely interpreted as being of terrestrial origin. The presence of sandstone channels within the red beds, as seen in the type area, is indicative of fluvial environments. Between Tandayapa and Nono are exposures which contain weak evidence of fluvial channels. Furthermore, despite the great thickness of sandstones present within the succession, there is no evidence of deposition from submarine turbidity currents.

The derived foraminifera described above are the only fossils previously described from the Silante Unit. The presence of angiosperm leaf fossils, which must be of terrestrial origin, in a thin sequence of possible lacustrine sediments, is clear and unequivocal evidence of non-marine, continental sedimentation in this part of the sequence.

Several lines of evidence suggest deposition under fluvial influences. Pedogenic horizons within red-bed sequences are typical of inter-channel areas of modern fluvial systems in semi-arid areas. In the Silante Unit these horizons consist of calcite concretions and silica pipes within red-bed sequences, and have been recognised in several areas. Heavy mineral placer horizons are also typical of fluvial environments, and magnetite placers have been identified within the Silante Unit along the Quito-Chiriboga and Nono-Tandayapa roads.

Substantial thicknesses of the unit, particularly along the Alóag-Santo Domingo road, consist of massive, poorly sorted, matrix-supported breccias and conglomerates, deposited by mass-flow processes. Such deposits are typical of terrestrial environments with moderate to high topographic relief and high rates of sediment supply, and are commonly triggered by volcanic eruptions (lahars). The western part of the unit in the type area, for example, consists of chaotic mass-flow breccias containing almost exclusively feldspar-phyric andesitic lithics in a feldspar-rich matrix, and was clearly triggered by a sudden input of large volumes of andesitic material into the depositional basin. Depositional patterns within such environments are commonly fault-controlled.

The absence of strained quartz and/or metamorphic clasts indicates that the provenance of the Silante Unit was non-metamorphic. The presence of plagioclase, pyroxenes, amphiboles and small amounts of K-feldspar within the matrices of the sandstones, conglomerates and breccias suggests sediment supply from a basic-intermediate volcanic source. This is supported by the presence of lithic clasts of feldspar-phyric andesites in the conglomerates and breccias. The euhedral nature of many of the feldspars, pyroxenes and amphiboles suggests proximity to the source area. The geochemical analyses of material from the 'Tandapi Unit' identified a calc-alkaline andesitic source (Kehrer and Van der Kaaden, 1979; Egüez, 1986; Van Thournout, 1991).

The provenance and sedimentological characteristics of the Silante Unit indicate deposition from a relatively proximal source of andesitic volcanic material in a terrestrial environment dominated by fluvial and mass-flow depositional processes, with possible lacustrine influences. These features might be considered typical of foreland basin and intermontane basin settings.

3.9 Macuchi Unit (PcE_M)

3.9.1 Distribution

The Macuchi Unit occupies most of the western half of the study area. It takes its name from the small mining town of Macuchi [717-9897] in the extreme south of the area along the La Maná-Pujilí road, where the amount and quality of exposure are unfortunately very poor.

The Macuchi Unit is present only on the south-western side of the Toachi-Toacazo Fault. North of Laguan [737-9939] this fault forms the eastern limit of the Macuchi; south of Laguan the eastern limit of the unit is a probable faulted contact with rocks of the Angamarca Group. The western contact of the Macuchi Unit is with the Quaternary terrace deposits of the coastal plain. In most areas this contact is a marked break of slope feature, and has been mapped almost exclusively from aerial photographs.

With one notable exception, the general degree and quality of exposure are poor. Most of the area lies between 250 m and 3500 m above sea level, and is covered by thick, primary forest. The exception is the ca. 14 km long section in the Río Toachi between La Unión del Toachi [7283-99656] and Hacienda Bonanza [7147-99693], along which there is almost continuous and spectacular (but in many places inaccessible) exposure.

3.9.2 Age

The base of the Macuchi Unit is not seen anywhere in the cordillera. Egüez (1986) reported an Early to Mid Eocene radiolarian fauna from a sedimentary sequence exposed in the Quebrada Milagro [714-9901], a few kilometres west of the type area, and an Early Eocene foraminiferal fauna from the Tenefuerte Limestone, exposed in the same quebrada. Egüez (op. cit.) also reported two K-Ar whole-rock ages of 41.6 ± 2.1 and 35.8 ± 1.8 Ma (Mid to Late Eocene) from basaltic andesite intrusions in the same area. From the north of the study area Egüez (op. cit.) described a thick sequence, named by him the Las Juntas Unit, of fine-grained, thin-bedded turbidites which yielded a Late Eocene radiolarian fauna. On the basis of their supposed Late Eocene age these rocks were stated by Egüez (op. cit.) to be equivalent to the Apagua Formation, but they are here interpreted as part of the Macuchi Unit. However, the supposed Late Eocene age is inconsistent with the Macuchi Unit being older than the Mid to Late Eocene Unacota Formation (see section 3.11.2), and remains problematic.

In summary the evidence indicates that at least part of the Macuchi Unit in its type area is of Early Eocene age. It is possible that the oldest parts of the sequence are of Palaeocene age, but this cannot be proven.

3.9.3 Facies

The Macuchi Unit contains a great variety of facies, most of which have transitional contacts, and all of which may be present within a very small area. Considering the sequence as a whole, as much as 90% consists of sedimentary rocks and the remainder of pillow lavas and high-level diabase intrusions. The main facies are described below.

3.9.3.1 Pillow lavas and pillow breccias: Discrete sequences of pillow lavas within the Macuchi Unit have been mapped in three areas, but are certain to be much more widespread. The geochemistry of these is discussed in section 3.9.6. In the type area very deeply weathered pillows are exposed in craggy ground on Loma Chiquinquira [7184-99028]. Unfortunately, the rocks are too deeply weathered for whole-rock geochemistry. This sequence is at least 100 m thick, and can be traced on the aerial photographs almost as far south as Macuchi village [718-9897] and as far north as Cerro Patalo [719-9911], a distance of some 14 km; pillow lava blocks found in the Río Munchipamba at [7195-99164] are almost certainly from this sequence.

Two mappable sequences of pillow lavas are present in the Río Toachi section. The western sequence is exposed at Finca Las Mercedes [7183-99662], and consists of basaltic to andesitic lavas with intercalated cherts. The eastern one is exposed between El Paraíso [7216-99653] and La Unión del Toachi [7277-99654] and consists of numerous sheets of pillow basalts up to 50 m thick, intercalated with lesser thicknesses of matrix-supported pillow breccias, coarse-grained poorly sorted sandstones of basaltic composition, and hyaloclastites. The sedimentary sequences between the pillow lava sheets are clearly locally derived from the same submarine effusive sources which produced the pillows, and commonly contain detached pillows. The lavas are typically fine-grained, plagioclase-rich, and commonly pyroxene-phyric, with highly vesicular rims. This sequence is spectacularly exposed immediately downstream from La Unión del Toachi at [7276-99653] and at other localities between here and El Paraíso, for example at [7261-99655, 7249-99654, 7243-99653 (figured in Plate 2a), and 7219-99650].

An isolated exposure of pillow lavas is present at Cooperativa Flor de los Ríos [6886-99314] east of Patricia Pilar, but does not form a mappable unit. These lavas are fine-grained basaltic andesites.

3.9.3.2 Debrites: These are very common throughout the Macuchi Unit and are the products of the collapse and redeposition by mass flow processes of the unstable margins of submarine effusive edifices. They are commonly associated with pillow lavas, but are present in other parts where pillow lavas are unknown, where they are commonly intercalated with poorly sorted, coarse-grained turbidite sandstones of basaltic to andesitic composition, and with hyaloclastites. The debrites themselves are unsorted, coarse, matrix-supported breccias containing clasts of broken pillows up to 1 m across. The analysed clasts have the same composition as the pillow lavas within the Macuchi sequence (see section 3.9.6, geochemistry of Macuchi), and consist of basaltic andesites or andesites, commonly pyroxene-phyric with vesicular margins.

Excellent debrites are exposed in the Río Toachi at Tinalandia [717-99675] (see Plates 2b and 3a), in the Río Blanco [7097-99433] at Comuna Monte Nuevo, and in the type area at [7163-99025]. In each of these localities the debrites are interbedded with volcanoclastic sandstones containing abundant vesicular basaltic/andesitic clastic material, and with hyaloclastites.

Plate 2a. Basaltic andesite pillow lavas. Macuchi Unit, Río Toachi at Alluriquín [7243-99652]. 'Up' to left

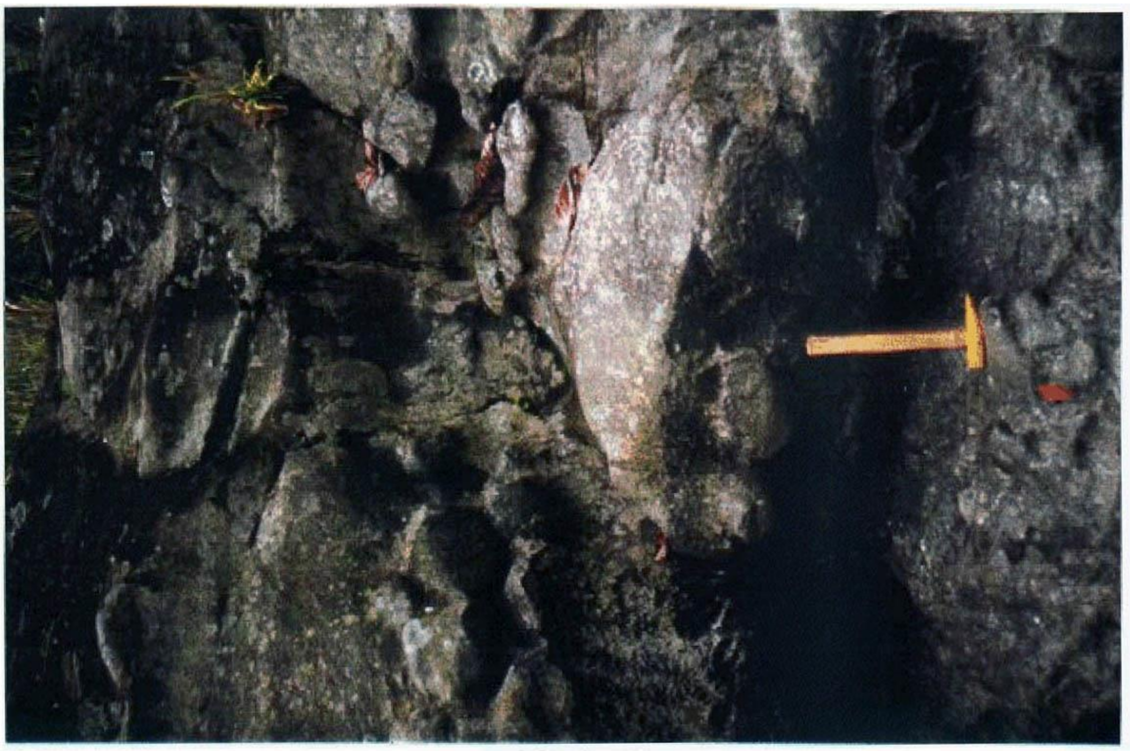

Plate 2b. Basaltic andesite pillow breccias and debrites. Macuchi Unit, Río Toachi at Tinalandia [7171-99675]. 'Up' to left

3.9.3.3 Limestone: A lenticular limestone body of Early Eocene age (Egüez, 1986), widely known as the Caliza Tenefuerte, is present at Tenefuerte [7152-99020], some 18 km north-east of La Maná. The limestone is used for making cement and reputedly for ornamental stone. Henderson (1981) estimated the thickness of the unit as 500 m, but this figure seems excessive; Egüez’ (1986) figure of approximately 300 m seems more realistic. Egüez (1986) assigns an Early Eocene age for the limestone, based upon foraminifera determinations.

The roadside exposures are poor, and better exposures are present in the Quebrada Milagro [7147-99002], from where Henderson (1981) described ‘massive greyish-white limestone…intercalated with lavas’. These exposures were re-examined during the present work, and the ‘intercalation’ was found to be a narrow intrusion of feldspar-phyric basalt/andesite within the hornfelsed limestone. Egüez (1986) published a K-Ar whole rock age of 41.6 ± 2.1 Ma from a ‘basaltic andesite’ which cuts the limestone. This isotopic age is consistent with an Early Eocene (or older) age for the Caliza Tenefuerte.

The intensely recrystallised nature of the limestone and its poor exposure make interpretation difficult. It could be a discontinuous, lenticular limestone sequence, or an olistolith derived for example from a fringing reef marginal to an island arc system.

3.9.3.4 Turbidites: Fine- to coarse-grained turbidites are very common within the Macuchi Unit, and are commonly associated with hyaloclastites and debrites. A sequence of interbedded coarse-grained turbidite sandstones, hyaloclastites and debrite breccias is present along the main La Maná to Pujilí road in the type area at [7163-99020], and is very well exposed along strike to the north in the Quebrada Tilipulo [7164-99028]. The succession consists of thin- to thick-bedded, medium- to coarse-grained, graded sandstones in T_{abc} sequences. The sandstones are lithic-rich, and of quartz-feldspathic (plagioclase) composition. The lithic component consists of highly vesicular, fine-grained, pyroxene-phyric andesite/basaltic andesite.

A sequence of fine-to coarse-grained turbiditic siltstones and sandstones has been mapped from just west of La Maná as far north as Río San Martín [720-9939], and is well-exposed along the Río Guadual between Guadual and Naranjal, north of Pucayacu. Thick-bedded, massive, coarse-grained sandstones and thin-bedded siltstones, interbedded with thin beds of debrite breccia are exposed, for example, in the Río Guadual at [7118-99251]. The sandstones are lithic-rich and poorly sorted, with abundant lithoclasts of highly vesicular andesite/basaltic andesite.

A sequence of finer-grained turbidites is very well exposed in the ríos Toachi and Pilatón at La Unión del Toachi [7280-99656] (see Plate 3b), and further south at San Francisco de Las Pampas [7281-99512]. This sequence was named the Las Juntas Unit by Egüez (1986) and correlated with the Apagua Formation on the basis of its Late Eocene radiolarian fauna (see above for further details). The succession is at least 250m thick, and consists of highly silicified mudstones, siltstones and fine-grained sandstones in T_{abce} cycles, with graded beds, weak sole structures, convolute laminations, flame and load structures all indicating overturning.

Plate 3a. Hyaloclastite debrites, with clasts of highly vesicular basaltic andesite. Macuchi Unit, Río Toachi at Tinalandia [7171-99675]

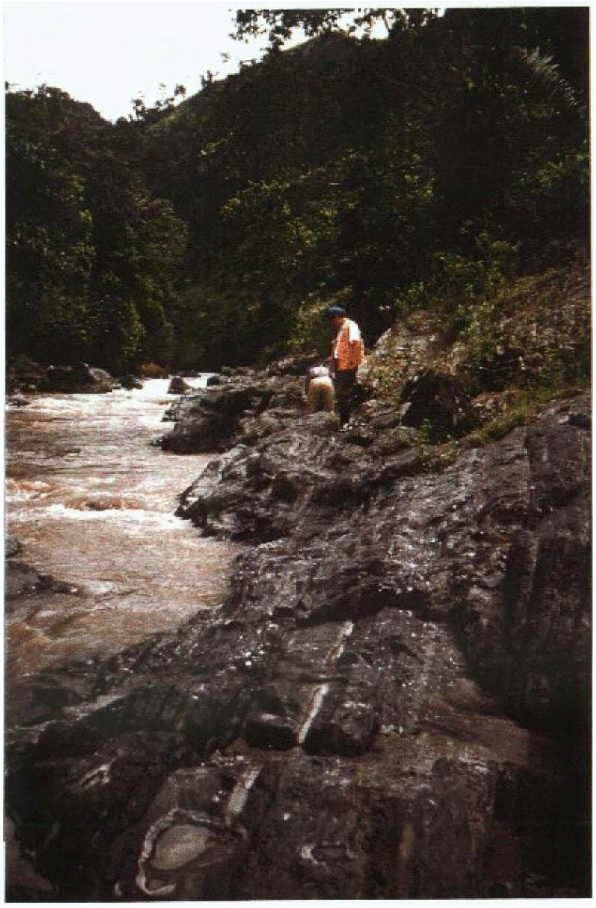

Plate 3b. Inverted, thin- to medium-bedded, fine-grained turbidites within Unidad Macuchi. La Unión del Toachi [7282-99648]

3.9.3.5 Diabase bodies: Diabase bodies, in the form of dykes and small intrusive bodies, are present at a few localities, and probably represent high-level intrusions. The best exposed are in the Río Toachi section (for example at [7172-99675]), where fine-grained diabase dykes up to 2 m across intrude a sequence of pillow breccias and hyaloclastite breccias. These dykes are almost certainly related to the igneous events that produced the pillow lava sequences present nearby in the Toachi section.

3.9.3.6 Ignimbrites: No ignimbrites were seen during field survey activities, but Dr. Arturo Egüez (pers. comm., March 1997) reports ‘acid ignimbrites’ at the surface and in cores from the La Maná area. Further detailed work elsewhere in the Macuchi Unit may reveal the presence of more.

3.9.4 Depositional environments

With the exception of the limestones and ignimbrites, all the facies present within the Macuchi Unit are the products of submarine basaltic to andesitic effusive eruptions. The pillow lavas, pillow breccias and diabase intrusions represent the near-vent eruptive products and possible magma conduits. The debrite breccias, fine- to coarse-grained turbidites, and hyaloclastites represent deposition on the slopes of the submarine volcanic edifices, with their crystal and lithic content derived from the same volcanic centres and eruptions.

The reported presence of ignimbrites within the Macuchi Unit is very significant to the interpretation of the sequence, clearly indicating subaerial eruptions and therefore a possible island-arc setting. The development of fringing reefs, possibly represented by the Tenefuerte Limestone, would be expected in a low latitude island-arc setting. This interpretation, based upon facies and mineralisation style alone, is strongly supported by whole-rock geochemistry (see section 3.9.6). Furthermore, Aguirre and Atherton (1987) interpreted the low-grade metamorphism of the Macuchi Unit as indicative of an ‘oceanic island arc generated contemporaneously with a marginal basin’.

3.9.5 Mineralisation

Extensive sulphide mineralisation is present in the Macuchi area and further north at La Plata [7291-99566]. This mineralisation is discussed in section 6 of this report, but is interpreted to be of the submarine exhalative type, and occurred around submarine effusive vents.

3.9.6 Whole-rock geochemistry

Fifteen samples from various locations and rock-types within the Macuchi Unit were submitted for whole-rock geochemical analysis, and the data is tabulated in Appendix 1. Of these, six are from pillow lava sequences, two are from probable high-level intrusions and the remaining seven are from large igneous clasts within monomict debrite breccias, and are probably pillow fragments. Fresh, unaltered material is very scarce because of weathering, and for this and other reasons (presence of phenocryst phases, vesicularity) the rock samples analysed are by no means ideal for whole-rock geochemistry. Nevertheless, the immobile element composition of these samples gives a valuable indication of the tectonic setting.

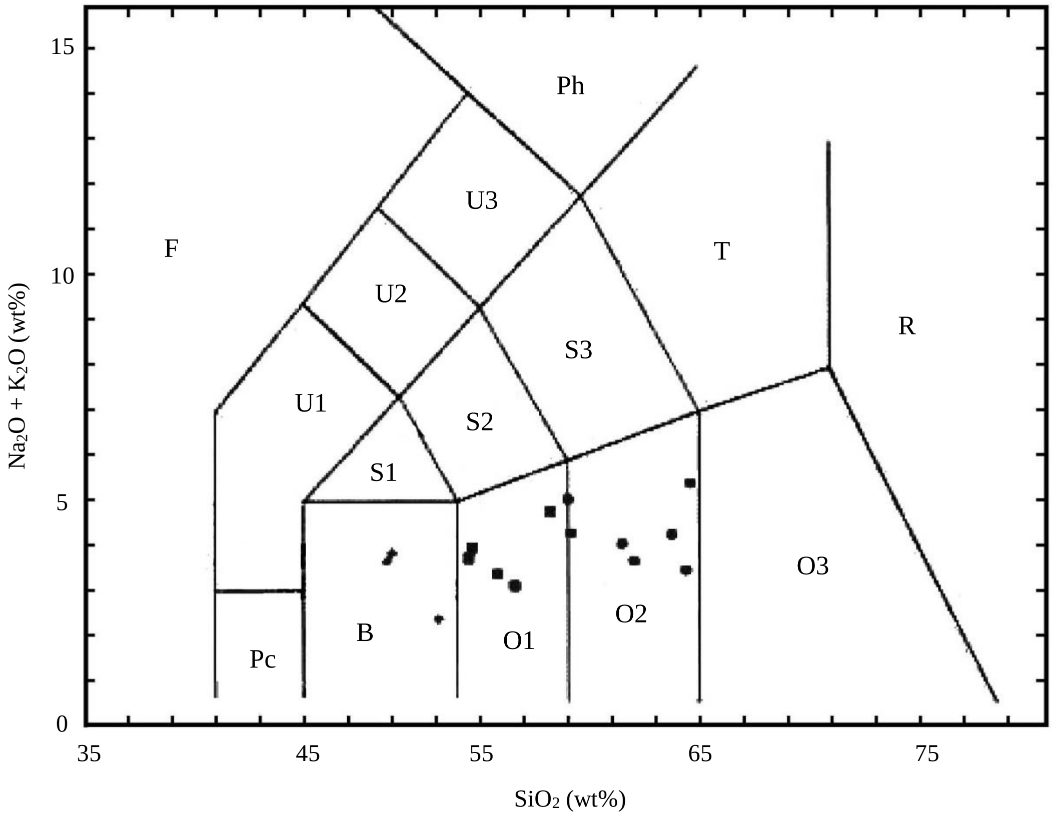

Figure 2. SiO_2 vs. $Na_2O + K_2O$ (Le Maitre, 1989); diamonds are basalts, squares are basaltic andesites and circles are andesites

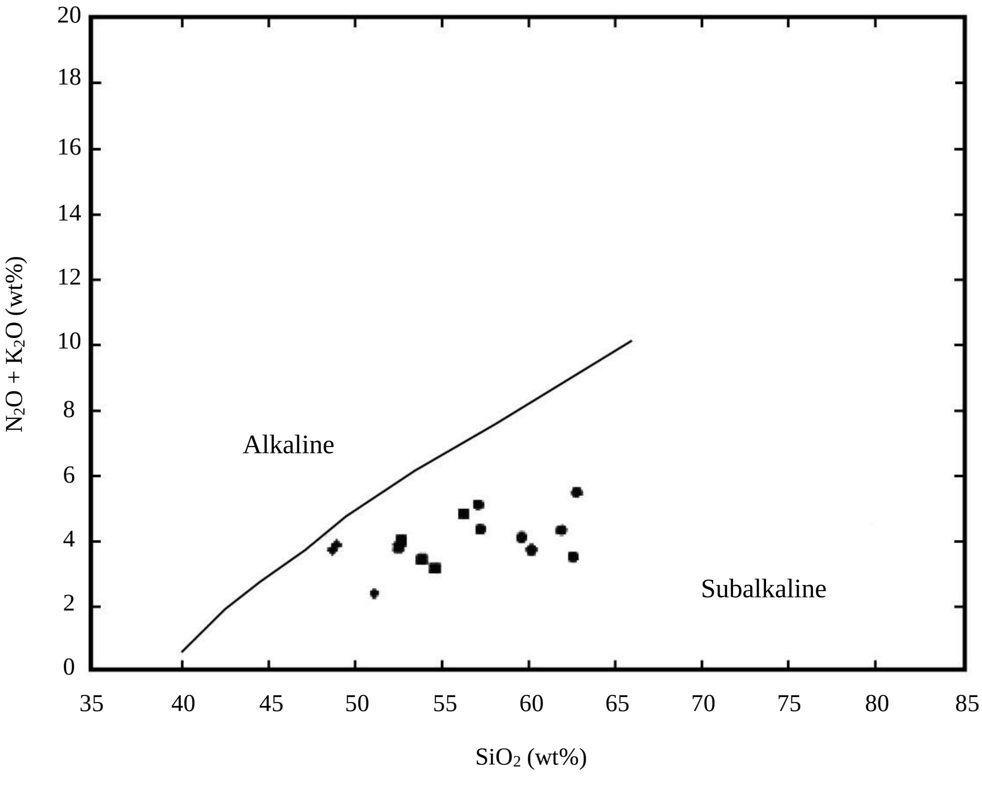

Figure 3. SiO_2 vs. $Na_2O + K_2O$ (Irvine and Baragar, 1971)

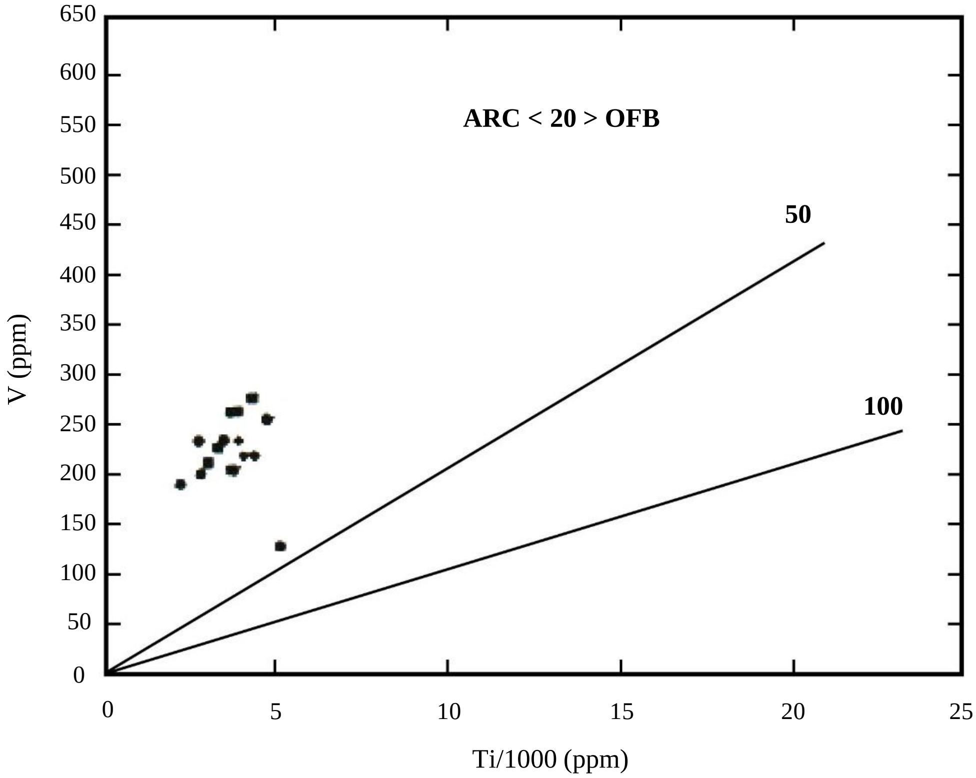

Figure 4. Ti/1000 vs. V (Shervais, 1982)

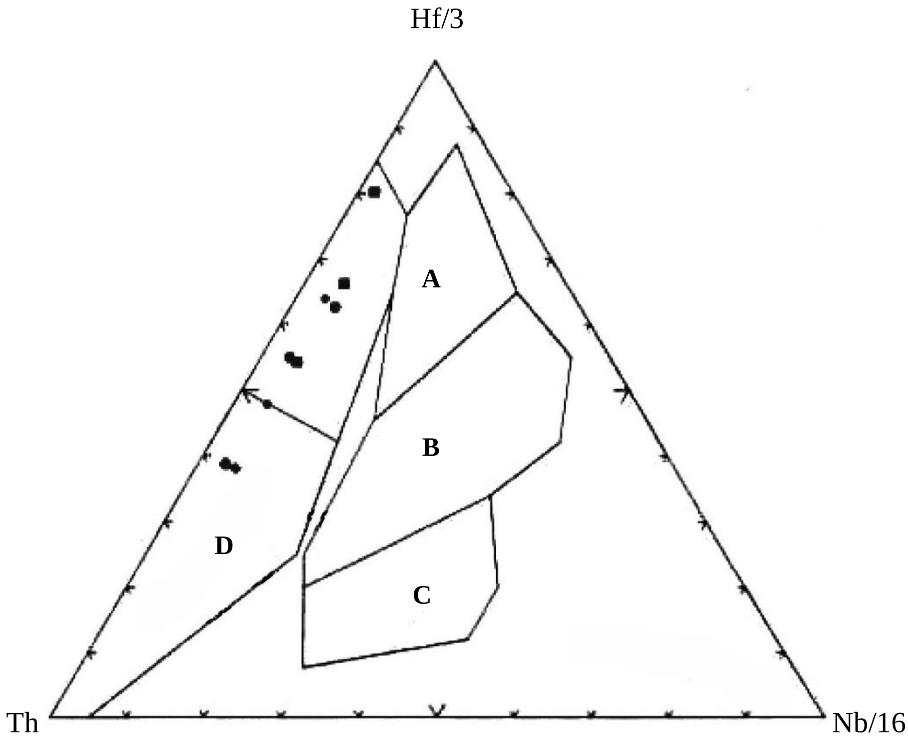

Figure 5. Hf/3 vs. Th vs. Nb/16 (Wood, 1980)

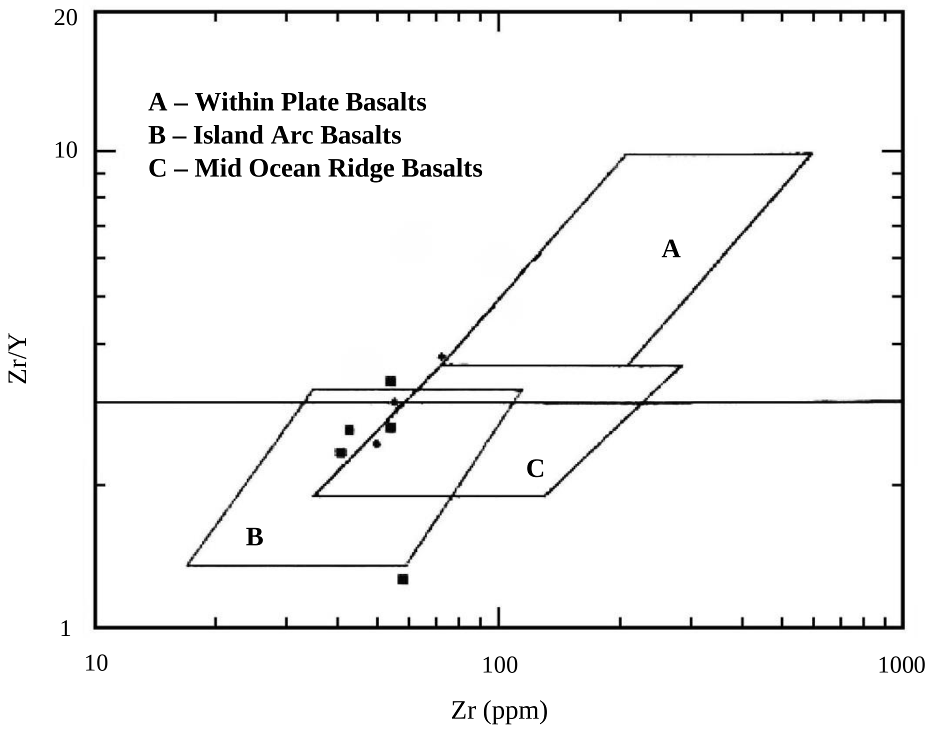

Figure 6. Zr vs. Zr/Y (Pearce and Norry, 1979)

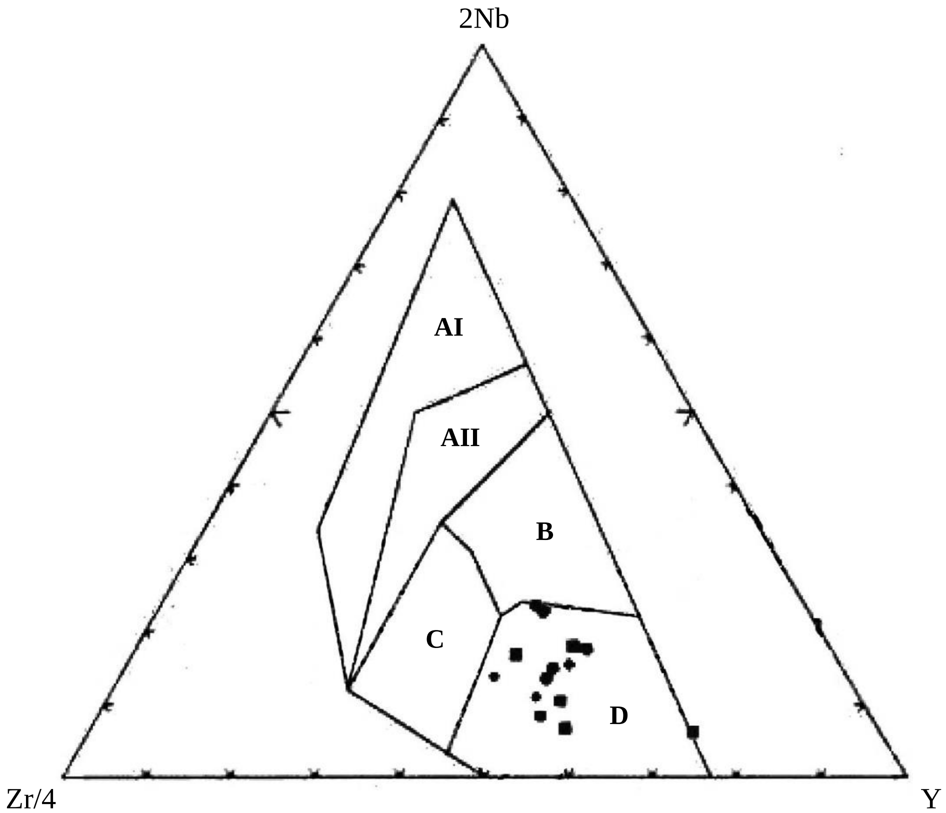

Figure 7. 2Nb vs. Zr/4 vs. Y (Meschede, 1986)

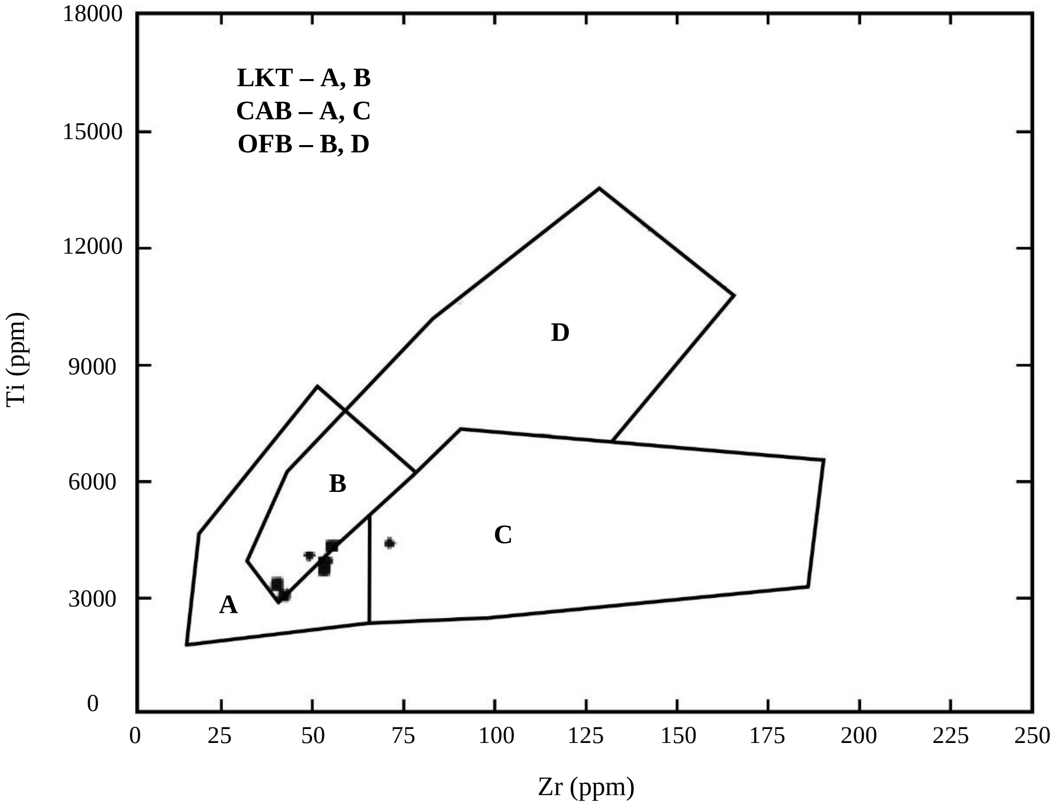

Figure 8. Ti vs. Zr (Pearce and Cann, 1973)

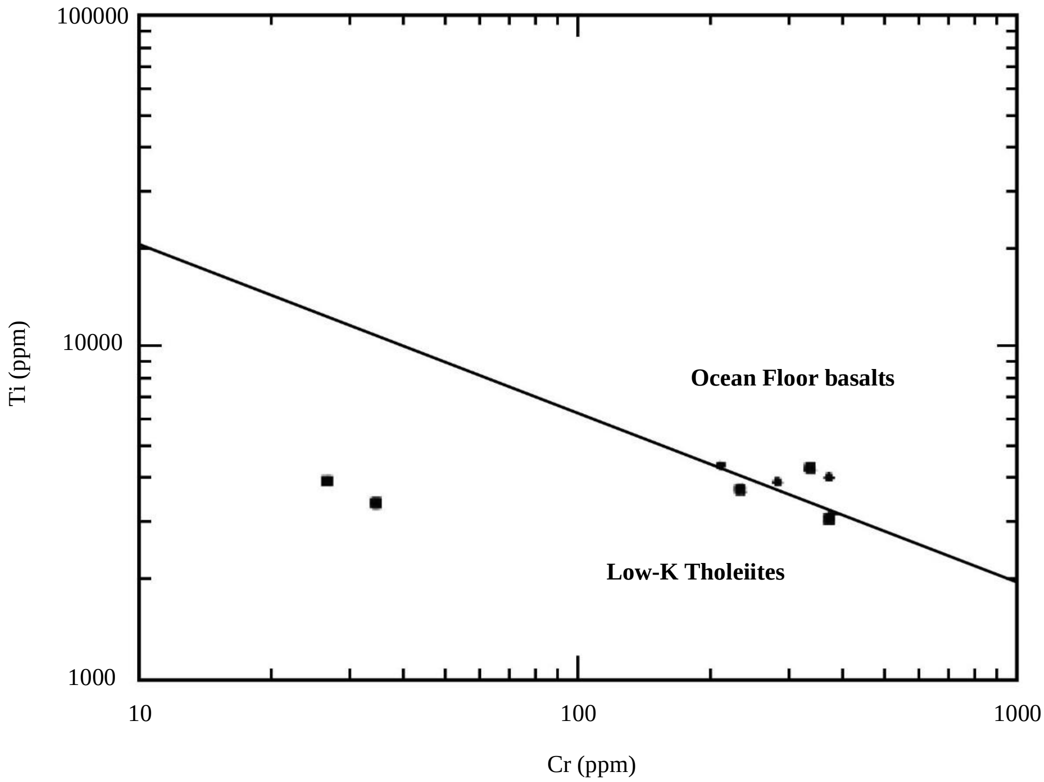

Figure 9. Ti vs. Cr (Pearce, 1975)

Seven of the samples are andesites, five are basaltic andesites and three are basalts (Figure 2); all are sub-alkaline (Figure 3). Most of the trace element discrimination plots show that the samples (with the exception of RH-276, RH-278B and RH-279B) do not belong to a mid-ocean ridge setting. The data fall very clearly into the arc basalt fields of the V vs. Ti/1000 (Figure 4; Shervais, 1982) and the Hf/3 vs. Th vs. Nb/16 plots (Figure 5; Wood, 1980). They also show clear arc affinities when plotted on the Zr/Y vs. Zr (Figure 6; Pearce and Norry, 1979) and the 2Nb vs. Zr/4 vs. Y diagrams (Figure 7; Meschede, 1986), though some samples fall into fields shared by arc basalts and MORB basalts. On the Ti vs. Zr plot (Figure 8; Pearce and Cann, 1973) two of the samples fall into the calc-alkaline basalt field.

On the Ti vs. Cr plot of (Figure 9; Pearce, 1975), the three basalt samples RH-276, RH-278B and RH-279B fall clearly into the ocean floor basalt field, the basaltic andesite RH-297 falls within the MORB field, and the two basaltic andesites RH-280b and RH-282b plot on the dividing line between ocean floor basalts and low-K tholeiites. The remaining two fall into the low-K tholeiite field. These six samples also have significantly higher MgO, Cr, Sr and Ni values than the remainder of the population, suggesting primitive basalt composition. Of the six, five are from a sequence of pillow lavas exposed in the Río Toachi between La Unión del Toachi [7277-99654] and El Paraíso [7215-99654], and the sixth is from an isolated locality in the Río Toachi at San Lorenzo [7313-99439]. Field relations indicate that the area of pillow lavas exposed between La Unión and El Paraíso is part of the Macuchi Unit, but that the geochemistry of this unit is atypical and suggestive of MORB or primitive basalts. It appears that these rocks are primitive basaltic lavas within a sequence otherwise dominated by andesites and basaltic andesites whose geochemical signature is indicative of an arc setting. They are primitive arc basalts (the major and minor element composition of some approaches that of boninites) or a slice of oceanic crust, part of the oceanic crust upon which the Macuchi arc was constructed.

These interpretations are entirely consistent with those of previous authors (e.g. Lebrat et al., 1985, 1987; Van Thournout et al., 1992), who recorded both MORB and island-arc tholeiites from the Macuchi Unit.

3.10 Saquisilí Unit (Pc_S)

3.10.1 Distribution

The Saquisilí Unit is restricted to the south-east of the area, where it is exposed in several quebradas which drain from the watershed of the cordillera into the inter-Andean graben between La Victoria and Saquisilí. The best sections are in Quebrada El Carnicero [7555-99006], Quebrada Maca Grande [755-9904], Quebrada Quila [7558-99063], and Quebrada Pusuchisi [7570-99082]. The unit is fault bounded to the east and west, and neither the base nor the top of the sequence are seen. The thickness of the unit is therefore unknown, but is at least several hundred metres.

3.10.2 Age

A foraminiferal fauna recovered from siltstones in the Quebrada Pusuchisi [7560-99071] during the present survey gives an age of ‘the latest part of the Early Paleocene and the earliest part of the Mid Palaeocene’ (Wilkinson, 1997).

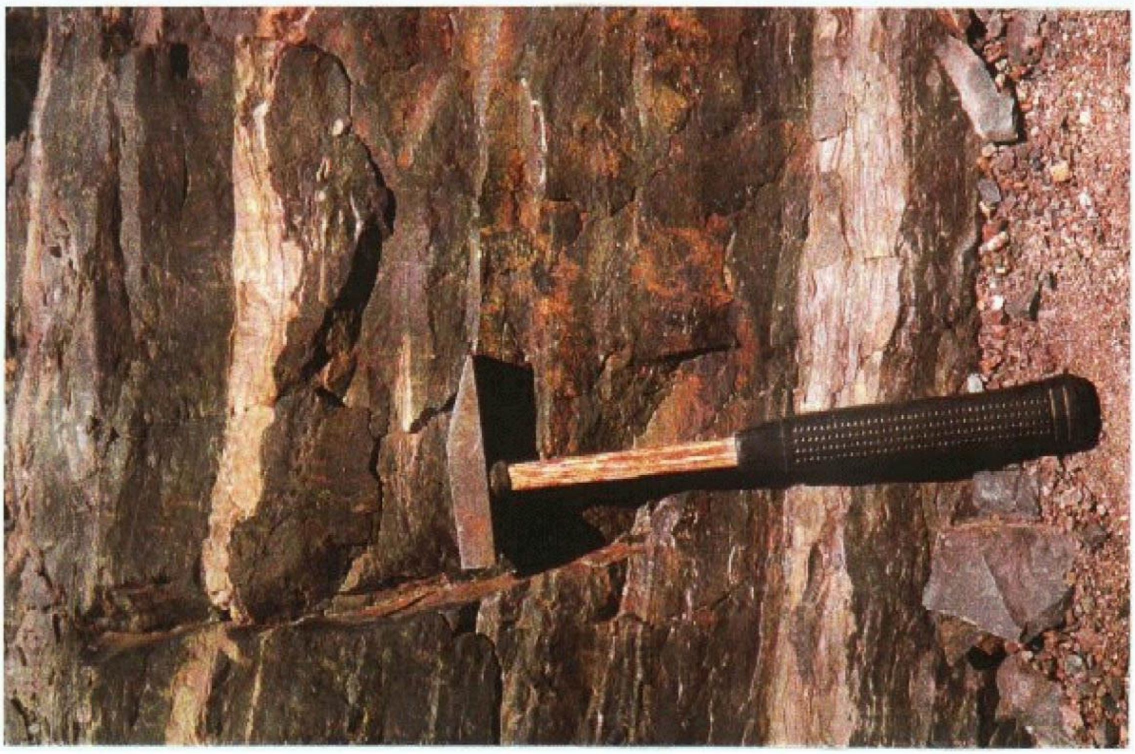

Plate 4a. Thin- to medium-bedded muddy turbidites with convolute laminated sandy beds showing loaded bases. Saquisilí Unit, Quebrada Pusuchisi [7560-99071]. 'Up' to left

Plate 4b. Sandstone lens within massive, fine conglomerates. Rumi Cruz Formation, Apagua [7316-98947]. 'Up' to left

3.10.3 Facies

The turbidite sequence consists of thin- to medium-bedded, grey to dark-grey, micaceous sandstones, siltstones, silty mudstones and mudstones, mainly in T_{bcde} sequences (see Plate 4a). Some beds are weakly calcareous. Coarse-grained, graded T_a units are uncommon, but fine- to medium-grained sandstones in parallel-laminated units (T_b) with current-rippled tops (T_c) comprise most of the sequence. Very coarse-grained sandstones seen in the Quebrada Maca Grande contain foliated lithoclasts, and are clearly derived from a source area containing a metamorphic component.

3.10.4 Depositional environment

The Bouma cycles of the Saquisilí Unit are typical of fine- to medium-grained, submarine turbidite deposition in a mid-fan environment, away from very coarse sediment supply.

3.10.5 Discussion

The Saquisilí Unit was attributed to the Yunguilla Unit on the Latacunga 1:100000 geological sheet (DGGM, 1980), and to the Apagua Formation on the 1:1000000 scale national geological map (BGS-CODIGEM, 1993).

3.11 Angamarca Group

This new lithostratigraphical unit comprises the Apagua Formation, the Gallo Rumi Formation (not present in this area), the Pilaló Formation, the Unacota Formation, and the Rumi Cruz Formation. The stratigraphical relationships of these units are shown schematically in Figure 10. The western contact of the Angamarca Group with the Macuchi Unit is interpreted to be a fault. The eastern contact with the Zumbagua Group is an unconformity.

3.11.1 Pilaló Formation (PcE_P)

3.11.1.1 Distribution: The Pilaló Formation is a volcanoclastic sedimentary unit, developed only in the extreme south of the area. It was named the Pilaló Unit by Egüez and Bourgois (1986) after the village of Pilaló [723-9895] along the La Maná to Latacunga road. The Formation is generally poorly exposed; the best exposures are to be found to the east of the village along the valley of the Río Chilcas/Pilaló, where a thickness of up to 1500 m is present. The contact of the Pilaló Formation with the underlying Apagua Formation is not exposed, but is interpreted to be concordant and conformable.

3.11.1.2 Age: There is no age evidence from the Pilaló Formation itself, but it is overlain, apparently conformably but possibly with a non-sequence, by the Unacota Formation of Mid Eocene age. To the south the Pilaló Formation is apparently underlain by sediments of Early to Mid Palaeocene age, although lithological correlations are complicated by extensive hornfelsing from the El Corazón pluton. In the Pilaló area the Pilaló Formation is intruded by a plagioclase-phyric andesite which yielded a K-Ar whole-rock age of 24.7 ± 1.2 Ma (=Late Oligocene; Egüez and Bourgois, 1986). The evidence is unclear, but appears to indicate that the Pilaló Formation is pre-Mid Eocene, probable of Palaeocene age.

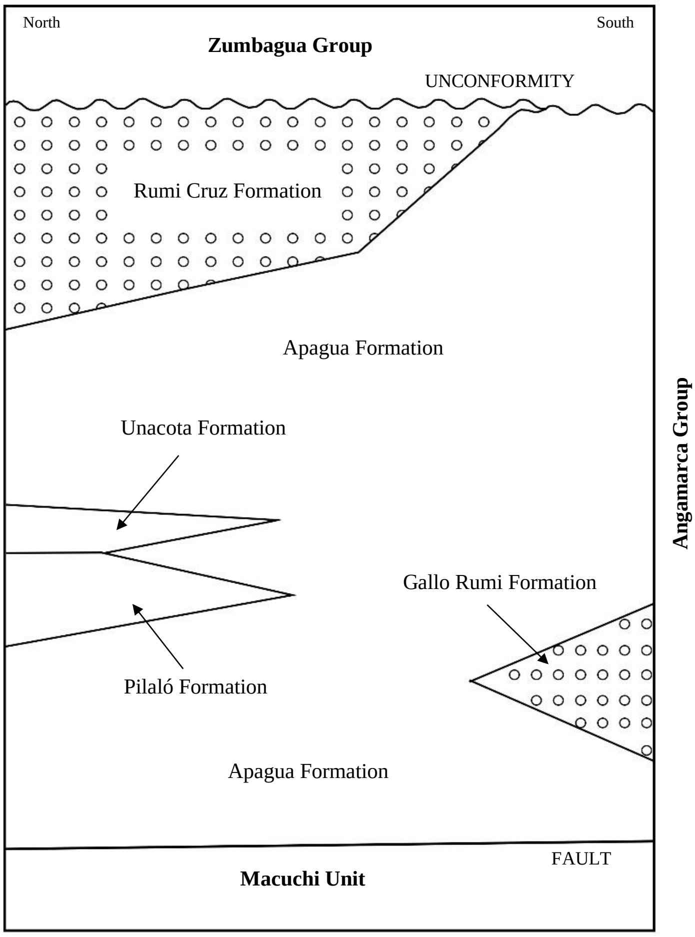

Figure 10. Stratigraphical relationships within the Angamarca Group (schematic and not to scale)

3.11.1.3 Facies

The Pilaló Formation appears to be entirely sedimentary. Egüez and Bourgois (1986) divided the unit into upper and lower parts, and also reported thin lavas in the lower part of the sequence, but their presence could not be confirmed during the present work. The unit consists of coarse-grained sandstones and poorly sorted, massive, matrix-supported breccias with clasts of igneous, mainly andesitic composition. Calcareous siltstones are present in the upper parts of the sequence. Igneous lithoclasts are generally very fine-grained and are commonly reddened. K-feldspar is present within some clasts and matrix. Most mafic minerals are altered to chlorite; pseudomorphs of pyroxene and amphibole are present.

3.11.2 Unacota Formation (E_U)

3.11.2.1 Distribution: The Unacota Formation is present on the high páramo in the extreme south of the area, just west of the village of Apagua. It dies out at or very near to 1°S. Its conformable contact with the overlying Apagua Formation is exposed along the La Maná-Latacunga road at [7282-98911], 3 km south-west of Apagua. South of the road the limestone forms a series of discontinuous, lenticular crags running south-west across the páramo. North of the road the Unacota Formation is exposed in the Río Chilcas [728-9895], where its conformable upper contact with the Apagua Formation is exposed, and its lower contact with the Pilaló Formation can be located on a narrow, but inaccessible stretch of the river. North of the Río Chilcas the limestone strikes north towards the now disused Cementos Cotopaxi quarries at Cerro Unacota [726-9801]. Boreholes drilled by this company indicate a maximum thickness of approximately 80 m here (Echeverría, 1977), but in the Río Chilcas the sequence could be considerably thicker.

3.11.2.2 Age: Abundant algal and foraminiferal evidence indicates a Mid to Late Eocene age (Egüez and Bourgois, 1986).

3.11.2.3 Facies: The exposures south of the La Maná-Latacunga road have not been examined in detail, but they have a morphology typical of algal mounds or reefs. Along the La Maná-Latacunga road the limestone is in contact with a small tonalite intrusion, and is almost completely recrystallised. Stromatolite-type algal mats are visible at the top of the sequence along the road section, indicating that at least part of the unit is a shallow water, biogenic limestone. The best exposures are to be found in the Río Chilcas. The upper contact of the limestone with the Apagua Formation is exposed in the river at [7291-98947], where thin bands of limestone are interbedded with thin-bedded, fine-grained, muddy and silty turbidites of the lowermost Apagua. Below the contact the limestones are thick-bedded, parallel-laminated sparites. The lower contact of the limestone is present in the river close to [7903-98951], but at this point the river section is inaccessible. Very large blocks of massive sparite choke the river gorge at this point. North of the Río Chilcas the limestone is present at the quarries of Cerro Unacota [726-9801], where massive micrites and sparites are exposed.

3.11.3 Apagua Formation (PcE_A)

3.11.3.1 Distribution: The Apagua Formation (Apagua Unit of Egüez and Bourgois, 1986) is best exposed in its type area along the La Maná to Latacunga road in the vicinity of Apagua. Further, isolated localities occur at Guayrapungu, along the Zumbagua to Chugchilán road, in an inlier beneath the stratovolcanic cone of Quilotoa, and in an inlier at Lahuan, north of Sigchos.

3.11.3.2 Age: The lower age limit of the Apagua Formation is known to be Mid Palaeocene (Wilkinson, 1997). The age of the youngest part of the Apagua Formation is post Mid Eocene, because it overlies the Unacota Limestone.

3.11.3.3 Facies: The lowest parts of the formation consist of thin- to medium-bedded, fine- to medium-grained sandstones with thin, dark grey siltstones and mudstones, in T_{bcd} sequences. Coarser-grained, graded T_a units are present but rare. The sandstones are typically fine-grained, well-sorted, rich in angular quartz, with common plagioclase. Coarse-grained sandstones are rare in the lowest few hundred metres but comprise most of the upper part of the Formation. They are graded, with weakly developed sole structures, commonly have pebbly bases, and represent deposition from high-density turbidity currents in T_{abc} sequences.

Dark grey, thin-bedded, sheared siliceous silty mudstone and mudstone turbidites exposed at [7440-99034] in the vicinity of Guayrapungu yielded a probable Early Eocene radiolarian fauna (Egüez, 1986). These rocks are believed to be an inlier of the Apagua Formation excised along a north-south trending regional fault.

3.11.4 Rumi Cruz Formation (E_{Rc})

3.11.4.1 Distribution: This Formation is best exposed to the south of the village of Apagua, where it forms a north-south trending ridge over 4000 m high.

3.11.4.2 Age: There is no direct age evidence, but a Late Eocene age is inferred because the Rumi Cruz is stratigraphically above the Unacota Formation of Mid Eocene age.

3.11.4.3 Facies: The Rumi Cruz Formation consists entirely of very coarse conglomerates and breccias, and coarse-grained sandstones (Plate 4b). Fossil wood fragments are common. The conglomerates are massive and very thick-bedded, and the beds are of laterally extensive, unchanneled, ‘sheet’ form. Aerial photograph interpretation shows that individual beds extend for hundreds of metres. They are both clast- and matrix-supported, with very well-rounded clasts up to 15 cm across. The breccias are massive and matrix-supported throughout. Coarsening-upward cycles are present in medium sandstone beds within the conglomerates-breccias. At least one, thin (up to 3 m) sequence of red siltstones is present within the conglomerate-breccia sequence in the type area, but farther south (between Guaranda and Pallatanga) these red-bed sequences are more extensive.

3.11.5 Depositional environments and provenance of the Angamarca Group

The Angamarca Group is a coarsening-upward basin-fill sequence which shows progradation from submarine fan to fan-delta. The interpretation of the Apagua Formation is relatively straightforward, with its facies associations of fine- to coarse-grained turbidites being typical of the lower and middle parts of deep water, submarine fans. In contrast the interpretation of the Rumi Cruz Formation is more difficult. The very high degree of roundness of the clasts within the sequence is clear evidence that the material is recycled, and a fluvial origin seems most likely. Conglomerates are common within submarine fan sequences, and are normally interpreted as submarine canyons or distributary feeder channel-fills. However, such channel-fill deposits have channel geometry and are normally of very limited lateral extent, in marked contrast to the Rumi Cruz conglomerates. It is unlikely too that the Rumi Cruz conglomerates are redeposited feeder channel deposits, because the conglomerates form an extremely thick sequence. Similarly, there is no definitive evidence from the Rumi Cruz conglomerates which indicates a fluvial environment of deposition. No clast imbrication has been recognised in the extensive exposures, and their matrix-supported nature suggests deposition by mass-flow mechanisms rather than by fluvial agents. The presence of coarsening-upward cycles in sandstones within the conglomerates is not definitive evidence of a fluvial environment, because such cycles are reported from submarine feeder channel sequences (e.g. Reading, 1986).

Nevertheless, the sheet-like nature and great lateral extent of the conglomerate beds, the presence of thin red-bed sequences towards the top of the Rumi Cruz Formation, and the presence of abundant wood fragments all indicate greater terrestrial influences in the highest parts of the Formation. A fan-delta (the marine extension of an alluvial/fluvial fan sequence) seems the most likely depositional environment for the Rumi Cruz, with mature clast material derived from a fluvially dominated hinterland being redeposited (possibly by mass flow mechanism) as laterally extensive sheets in relatively shallow water. The red-bed sequences may represent terrestrial deposition during times of brief emergence.

The Unacota Formation is a marine limestone interval within the siliciclastic turbidite fan sequence. The presence of *in situ* stromatolite mounds indicates a water depth of <200 m (the photic zone). The limestones therefore represent a significant shallowing of the depositional basin, with the development of Waulsortian-type reef mounds, and possible temporary emergence. The presence of limestones of the same age within the Tertiary basins of the Oriente and the Progreso Basin suggests a global-eustatic low sea-level stand in the Early to Mid Eocene.

Apagua sandstones are typically feldspathic, contain little muscovite and biotite and virtually no mafic minerals. The conglomerates are polymictic but of generally uniform composition, containing abundant metamorphic white quartz of probable metamorphic origin, black chert, rare muscovitic granitoids, and some metasedimentary(?) clasts. The source of the enormous quantities of quartz and chert is problematic, but undoubtedly these materials were subjected to prolonged transport/erosion prior to their incorporation into the Rumi Cruz conglomerates. The presence of rare granitoids and metasedimentary clasts indicates a pre-Rumi Cruz magmatic event in the source area.

The petrographical continuity and similarity of the lowest and highest parts of the Apagua Formation and of sandstones within the Rumi Cruz Formation suggest that the Angamarca Group represents an apparently continuous sedimentary depositional event, interrupted by deposition from a discrete andesitic volcanic source (Pilaló Formation) and limestone deposition in response to a regional or global eustatic low-stand (Unacota Formation).

3.12 Zumbagua Group (M_Z)

3.12.1 Distribution

The name Zumbagua Group is given to the sequence of volcanosedimentary rocks depicted on the 1:1000000 scale National Geological Map (1993) as ‘Volcánicos Pisayambo’. It takes its name from the village of Zumbagua [734-9894] along the main road between La Maná and Pujilí. It is restricted to the south-east of the map area, where it covers much of the Latacunga and Sigchos 1:100000 sheets, and is absent from the area to the north-east of the Toachi-Toacazo Fault. Exposure is generally good, especially along the Zumbagua to Pujilí road section and on the high páramo to the south-east of Sigchos and the north-west of Pujilí.

The sequence unconformably overlies the Apagua Formation, and the discordant contact can be seen just west of the village of Zumbagua at [7328-98940]. The top of the sequence is not seen, but a thickness of at least 1500 m is present in the area south-east of Sigchos.

3.12.2 Age

The precise age of the Zumbagua Group in the present area was unknown until this study. Five zircon fission-track ages (Steinmann, 1997; see Table 2) were obtained from samples of poorly sorted, coarse-grained sandstones and the matrices of matrix-supported breccias. The relatively high errors are the result of small zircon populations and/or low uranium contents. However, the data indicate that the Zumbagua Group is of Mid to Late Miocene or younger age.

The Zumbagua Group is intruded by a number of microtonalite plutons, the largest being immediately south of Zumbagua (exposed at, for example, [734-9893]); this intrusion carries a probable roof pendant of Zumbagua Group rocks. An age of 6.27 ± 0.17 Ma (late Miocene) was obtained by K-Ar mineral separate analysis of the microtonalite at Zumbagua (locality RH-351, [7338-99941]). In summary the age evidence indicates that the Zumbagua Group is of Mid to Late Miocene age.

Table 2. Zircon fission-track ages from the Zumbagua Group. Confidence is rated on a scale of 1-5, with 2 indicating good quality and good confidence in age, 3 indicating acceptable age, and 4 indicating low confidence. Data from Steinmann (1997).

Sample	Coordinates	Age (Ma)	Confidence
RH-60	7331-98938	15.5 ± 1.2	2
RH-67	7351-98994	8.4 ± 1.2	3
RH-76	7430-99070	15.3 ± 1.9	3
RH-99	7432-99143	10.9 ± 0.9	3
RH-342	7414-99184	14.5 ± 2.7	4

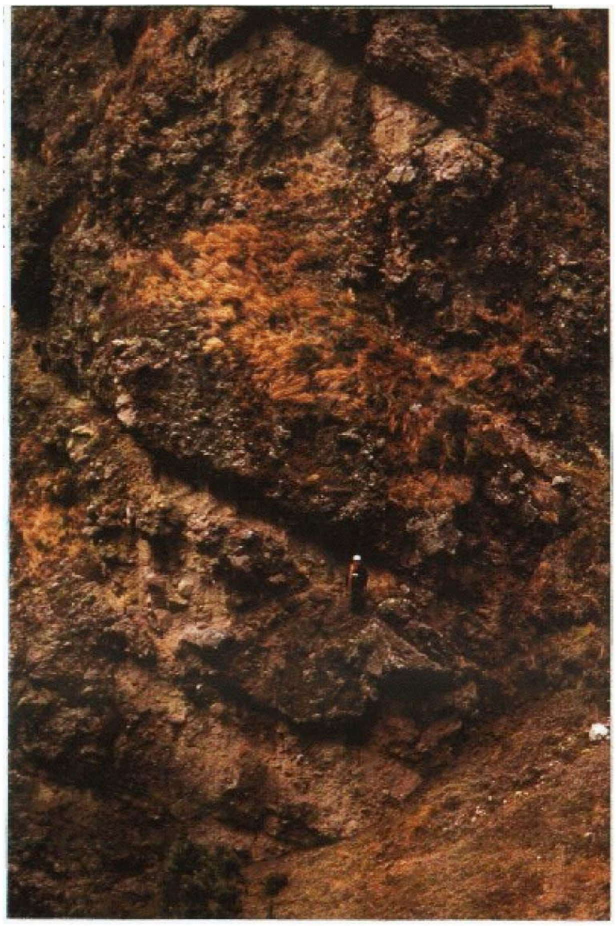

Plate 5a. Very thick-bedded, massive debrites. Zumbagua Group, Michaca [7371-98903]

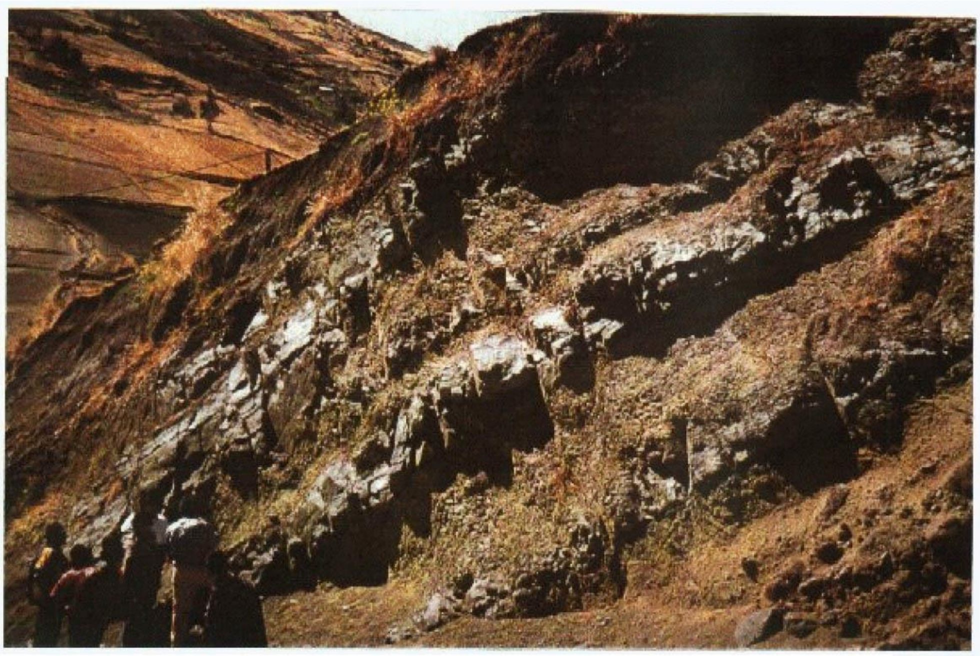

Plate 5b. Medium- to thick-bedded, fine-grained, possibly lacustrine turbidites with fluvial? conglomerates. Zumbagua Group, Tigua [7394-98948]

3.12.3 Facies

The rocks of the Zumbagua Group are predominantly very coarse-grained, very poorly sorted sandstones and unsorted, matrix-supported debrite breccias, in beds up to several metres thick. The sandstones are tuffaceous (see below), but their poor sorting suggests that they have been extensively reworked, and no primary air-fall tuffs have been recognised. The breccias are typically massive and chaotic, containing clasts ranging in size from a few millimetres to metres across (see Plate 5a). The thickest units form conspicuous, mappable, topographical features on the páramo south-east of Sigchos (for example at Cerro Guingopana [743-9914]), where debrite breccias are present in units (possibly amalgamated) at least 15 m thick. These breccias are the product of mass-flow processes: their exclusively igneous clast population and the euhedral nature of crystals within the matrix suggest that they may be lahars. Conglomerates containing well-rounded cobbles and boulders are also present (for example, [7394-98948] along the Zumbagua to Pujilí road). These conglomerates are weakly imbricated, and probably represent fluvial deposition: intercalated fine-grained, well-sorted, quartz- and feldspar-rich sandstones with loaded bases may be lacustrine turbidites (see Plate 5b).

The sandstones are typically lithic- and crystal-rich, with abundant quartz, euhedral plagioclase (commonly zoned) and K-feldspar, amphibole and rare biotite (see, for example, thin sections RH-45, 47, 54, 55, 60, 73). The lithic material within the sandstones, breccias and conglomerates is almost exclusively igneous, of andesitic, dacitic and rhyolitic composition (see, for example, thin sections RH-109a, b, c, d and e). Welding foliations are present within some clasts, indicating a probable subaerial volcanic source. Wood fragments are very common within the debrites, and a 2 m length of a tree trunk can be seen within a massive debrite bed at [7362-98946], between Zumbagua and Tigua (Plate 6a). A silicified tree trunk was found in the Quebrada Macas Grande, La Victoria [755-9904]; it is possible that this trunk was preserved in an ignimbrite eruption, but ignimbrites have not been seen in situ. Poorly sorted sandstones of the Zumbagua Group in the La Victoria area (for example in Quebrada Picisi [7555-99985]) contain locally derived clasts of ultrabasic rocks derived from the Pujilí Unit. This indicates that the rocks of the Pujilí Unit were exposed during that time.

3.12.4 Depositional environment

The presence of possible fluvial and lacustrine horizons, the abundance of wood material, and the absence of indicators of marine deposition suggest a terrestrial depositional environment for the Zumbagua Group, with mass-flow being the main depositional process. A substantial part of the sequence may consist of relatively locally derived, volcanically triggered lahars. The great thickness of many of the breccia units may be indicative of flow confinement, which would suggest deposition in an environment with substantial pre-existing topography, perhaps an intermontane basin setting, fed by a subaerial volcanic source of andesitic to rhyolitic composition.

3.13 Quaternary deposits

3.13.1 Quaternary volcanic deposits, undifferentiated (Q_V)

At least seven Quaternary volcanic centres, some of which are known to have had more than one source, are present within the area. From south to north these are Quilotoa (active), the Illinizas, Cerro Almas Santas, Cerro Corazón, Cerro Minasguilca Chico, Cerro Atacazo and Pichincha (active). Two more active volcanoes, Pululahua and the magnificent snow-capped stratovolcano Cotopaxi, lie within a few kilometres of the northern and eastern limits of the area. The enormously complex products of these volcanic centres, comprising tuffs, ashes, pyroclastic flows, lahars and lavas, are very extensive in the eastern half of the area. They have not been systematically mapped or studied in any detail during the present study, but an excellent summary of the Holocene activity of most of these volcanic centres is given by Hall and Mothes (1994, and references therein). Except for the extensive and spectacular pyroclastic flow deposits of Quilotoa and the Illinizas (see Plate 6b) in the areas between Zumbagua, Sigchos and Toacazo, which were identified and mapped from aerial photographs, the limits of the Quaternary volcanic deposits have been taken from existing published sources, mainly the Latacunga, Machachi and Quito 1:100000 scale geological sheets.

Based on published isotopic ages these rocks are thought to be of Quaternary age. However, it is possible that the activity of some of the oldest centres began in Pliocene times. Egüez (1986), for example, describes the deposits of Cerro Almas Santas as being of Pliocene and Quaternary age, but the evidence upon which this interpretation is based is unknown.

3.13.2 Quaternary terrace deposits (Q_T)

Very extensive Quaternary terrace deposits overlie the Cretaceous-Tertiary basement rocks in two main areas within the cordillera. The limits of the terraces have been mapped from aerial photographs, and their deposits have not been studied in any detail. However, from a cursory examination of a large number of exposures in several different areas, it is clear that a substantial proportion consists of lahars derived from the Quaternary volcanic centres along the western margin of the inter-Andean graben; the remainder is largely of fluvial origin. Following the Nono 1:50000 scale geological sheet, the name Unidad San Tadeo has been applied widely to these deposits. The Quaternary terrace deposits of the coastal plain may contain a lesser proportion of lahar material. The extent and probable sources of the main terrace deposits are described briefly below.

In the present area the southernmost terrace sequence within the cordillera is present between the ríos Toachi and Sarapullo, south of the Alóag-Santo Domingo road (see Manuel Cornejo Astorga 1:50000 sheet). From the dissected terrace remnants which lie alongside the course of the Río Toachi towards Santo Domingo it is clear that the former extent of the terraces was much greater. At its broadest the main terrace is some 10 km wide, and the maximum thickness of the sequence is at least 300 m, possibly as much as twice this figure. From the geometry of the terrace deposits it is clear that they were fed by a fluvial system whose course lay approximately along that of the modern Río Sarapullo around [746-9940] due south of the village of Tandapi. The extinct volcanoes of Cerro Corazón, the Illinizas, and possibly Cerro Almas Santas would have supplied material to the terrace system in the form of lahars. (Since the age of the earliest activity of these volcanoes is unknown with certainty, it is possible that the oldest parts of the terraces are of Late Pliocene age).

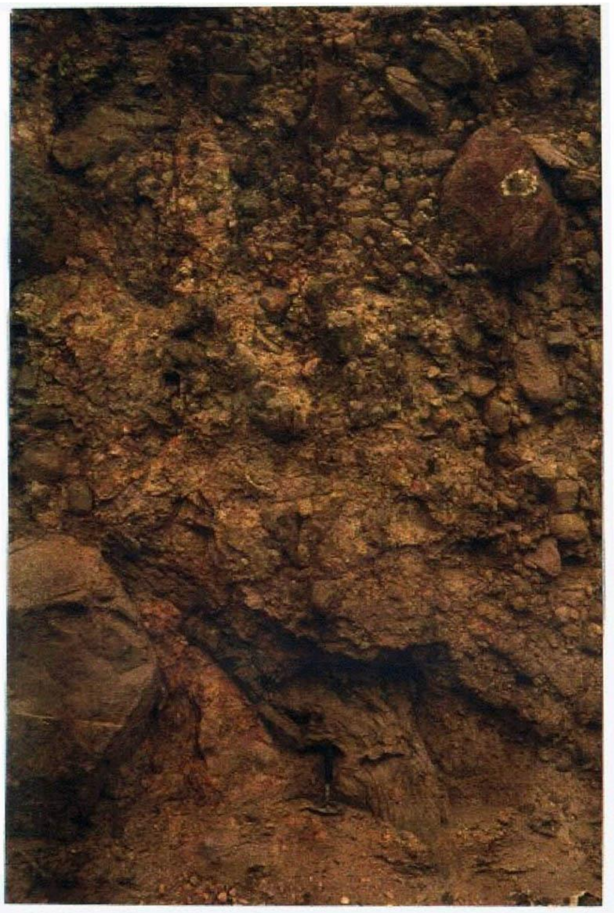

Plate 6a. Carbonised tree trunk (immediately above hammer) within massive debrites and conglomerates. Zumbagua Group, Zumbagua [7358-98938]

Plate 6b. Quaternary ignimbrites from Quilotoa volcano filling valley topography north of Zumbagua [734-9894]. The rim of the caldera forms the distant horizon

An equally extensive terrace system is present further north, between the valleys of the ríos Cinto [750-9986] and Saloya south of Mindo. The thickness of these terrace deposits could be as much as 600 m. Similarly, from the geometry of the terraces it is clear that they were fed by fluvial systems which followed the courses of the modern ríos Saloya and Cinto. The main sources of the material would therefore have been the volcanic centres of the Pichincha massif and Cerro Atacazo.

To the west of Mindo the Cinto-Saloya terrace system amalgamates with another system whose main feeders lie to the north of the present area and include the Río Guayllabamba, supplied by the Quaternary volcanic centres Cotacachi, Cuicocha, Huanguillaro and Pilavo. A few kilometres north-west of Mindo, where the ríos Saloya and Mindo converge to form the Río Blanco, these terrace deposits are at least 400 m thick. These amalgamated terrace deposits to the west and north-west of Mindo are vast: on the 1:1000000 scale National Geological Map (1993) they are said to be up to 1000 m thick.

3.13.3 Quaternary alluvium (Q_A)

Small areas of alluvium have been mapped along major river valleys, such as that of the Río Toachi. In contrast to the Quaternary terrace deposits these minor alluvial deposits are the products of fluvial deposition from the modern rivers to which they are immediately adjacent.

Alluvium of probable marine origin is very extensive along the western limit of the area, but in some areas (e.g. north of La Maná) is known to contain lahar horizons (see section 4.1 for further details).

3.13.4 Quaternary colluvium (Q_C)

Colluvium covers most of the steep slopes in the area, especially the western-facing slopes which experience very high rainfall. A thick, mappable colluvial deposit fills the valley of La Esperanza between approximately 1300 m and 2700 m. Its limits have been mapped from aerial photographs, and it has not been studied in detail. However, it appears from a number of landslides and resultant debris flows that occurred during the time of the survey that this deposit is still accumulating. Rapid and extensive deforestation in this and other areas seems likely to increase the frequency and size of landslips, and the accumulation of colluvial valley fills.

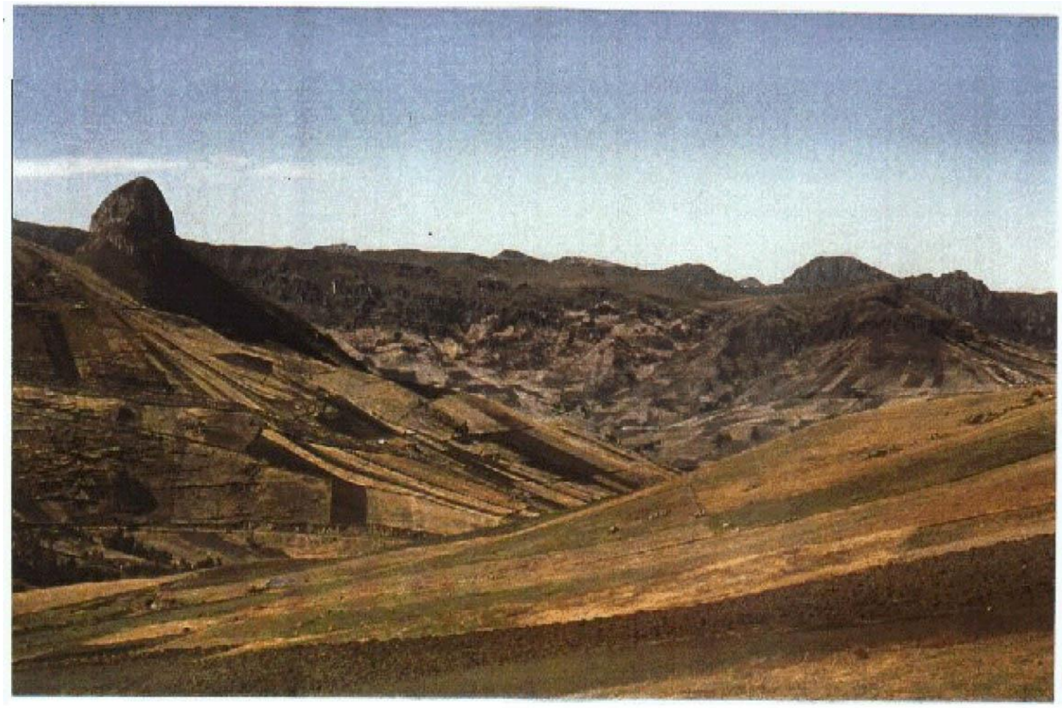

Plate 7a. A Miocene microtonalite stock forms the conspicuous rocky peak on the left, while further Miocene microtonalites form the craggy hills in the far distance on the right. The well-featured hillside in the middle distance consists of volcanosedimentary sequences of the Zumbagua Group. View south-west from Huaghaloma [741-9899]

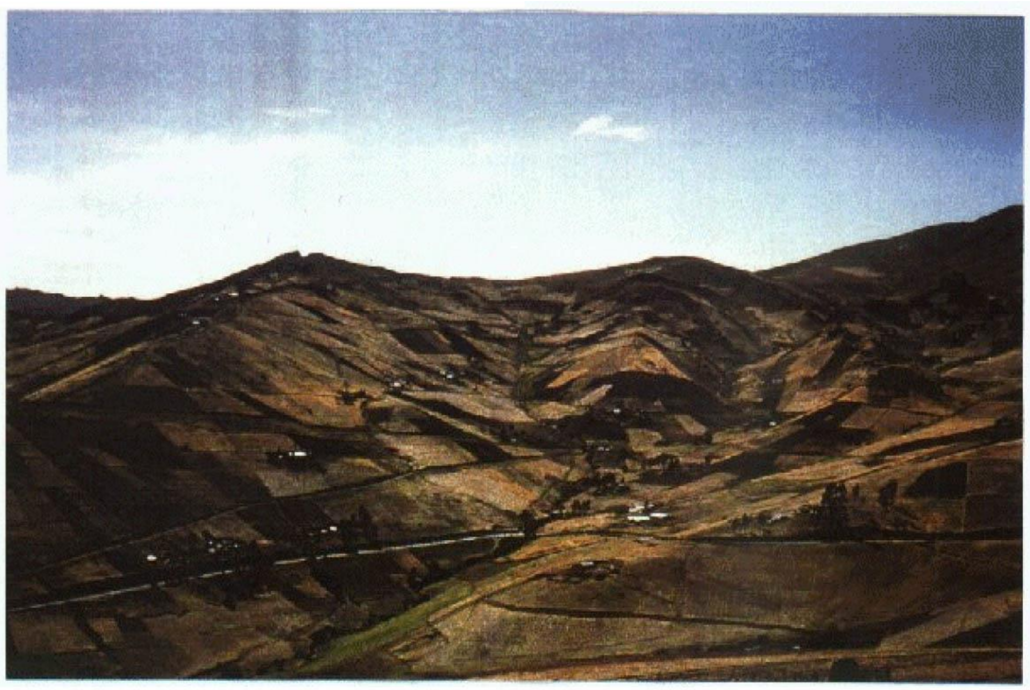

Plate 7b. Gentle open anticlinal folding of the Zumbagua Group at Chinibacuchos; view south-east from [7380-98948]. The anticlinal axis runs approximately along the small river valley in the centre of the photograph, and the topographic features show opposing dips on the fold limbs

4. INTRUSIVE ROCKS

There are three main groups of intrusive rocks in the area. In the west, mainly within the Macuchi Unit, is a suite of I-type (Ing. Pablo Duque, pers. comm.) coarse-grained granitoid rocks; in the south-east around Zumbagua and Tigua is a suite of porphyritic microtonalites; and in the north-west, mainly within the Mulaute Unit, is a suite of diorites, the two largest of which are foliated. Miscellaneous minor intrusions, which could be related to Pliocene or younger volcanism, are present mainly in the eastern half of the area.

4.1 I-type granitoids

Most of the granitoid plutons in the west of the area are very poorly exposed, and some have been identified only through evidence of river floats. The presence of four large plutons depicted on the published Valencia 1:100000 scale sheet could not be confirmed during the present survey. A large ‘granite’ pluton is shown in the Cordillera de Yungañan [710-9893] east of La Maná, but no evidence of granitoid blocks was seen in the ríos Puembo Chico and San José which drain the cordillera. Another large ‘granite’ pluton is shown within the Cordillera Tilinche, but similarly there is no evidence of granitoid blocks in the ríos Tilipulo [716-9902] and Munchipamba [719-9916] which drain the area. Granitoid intrusions are also shown in the vicinity of Estero Pope [795-9913] and the Río Tonglo [702-9916]. At these latter two localities, there are extensive lahar deposits containing coarse-grained, probable Quaternary acid to intermediate lavas. It is thought that the presence of granitic bodies in these localities was misinterpreted from these lava blocks.

Petrographically there is little variation between the major mapped plutons which are generally coarse-grained hornblende and biotite bearing granodiorites. From the available evidence there appears to be considerable age variation (see Appendix 2). K-Ar analyses of hornblende and biotite mineral separates from the Río Quindigua granodiorite [7196-99169] gave ages of 13.31 ± 0.44 Ma and 14.80 ± 0.14 Ma respectively (Mid Miocene). K-Ar analysis of a hornblende separate from the nearby Río Hugshatambo granodiorite [7106-99195] gave an age of 38.09 ± 0.39 Ma (Late Eocene). The Chaupicruz granodiorite [7203-99973] gave a zircon fission-track age of 7.0 ± 0.3 Ma (Late Miocene); Egüez (1986) published a K-Ar whole-rock age of 12.0 ± 0.6 Ma (Mid to Late Miocene) for this intrusion. Whole-rock geochemical data for the Río Hugshatambo and Río Quindigua intrusions are presented in Appendix 1.

4.2 Porphyritic microtonalites

A suite of porphyritic microtonalites containing hornblende and zoned plagioclase phenocrysts is present in the south-east of the area and is well exposed around Zumbagua and Tigua (see Plate 7a), where it forms a series of craggy peaks up to 4300 m high. K-Ar analysis of a hornblende mineral separate from the large intrusion at Zumbagua [7338-98941] gave an age of 6.27 ± 0.17 Ma (late Miocene).

4.3 Foliated diorites

At least two very poorly exposed, foliated, coarse-grained diorite bodies are present in the north-west, within the Mulaute Unit. One is present south of Cooperativa Mar de La Tranquilidad [e.g. 7340-99698] and has an apparently elongate north-south form. The other has not been found at outcrop, but occupies a forested area north of the Río Cocaniguas [733-9993]. Petrographically the rock consists predominantly of quartz and amphibole aggregates comprising hornblende cores and actinolite overgrowths defining the foliation. The presence of two distinct amphibole phases and a strong foliation suggests that the actinolite overgrowths are secondary and were produced by hydration simultaneously with the deformation event which produced the fabric. Alternatively, the intrusions may be syn-tectonic, intruded into an active shear zone. K-Ar analysis of a hornblende mineral separate from this rock gave an age of 48.28 ± 0.55 Ma. This age is believed to represent the age of deformation.

4.4 Other intrusions

At least four further diorite bodies have been recognised between Cooperativa Mar de La Tranquilidad and the Alóag-Santo Domingo road. Three of these are very poorly exposed along the old Quito-Santo Domingo road, but the fourth, the La Esperie intrusion, gave a K-Ar whole-rock age of 38.6 ± 1.9 Ma (Late Eocene; Egüez, 1986).

In the extreme south of the area between Pilaló and Zumbagua [e.g. 724-9893] is a strongly porphyritic microdiorite with very large phenocrysts of zoned plagioclase. A much smaller body of the same rock is exposed in the nearby Río Chilcas at [7280-98952]. Egüez (1986) described this rock as a ‘proto-intrusion’ related to the Pilaló Unit, and published a K-Ar whole-rock age of 24.7 ± 1.2 Ma (Late Oligocene). The microdiorite is here not believed to have any close relation with the Pilaló Unit.

Fine-grained basaltic andesites are exposed in and around the Río Potoa [7515-98938], southwest of Pujilí. These rocks have been interpreted as part of the Macuchi Unit (e.g. Egüez, 1986). However, relative to the basaltic andesites of the Macuchi Unit the Pujilí basaltic andesites have high values of TiO_2, K_2O, Ba, Rb, Sr, Zr, and there is little geochemical similarity between the two (see Appendix 1). They are therefore interpreted to be locally developed basaltic andesite intrusions, unrelated to the Macuchi Unit.

5. STRUCTURE

5.1 Faulting

Faults are an essential component of the regional structural interpretation, but are rarely exposed. Kinematic indicators seen throughout the area suggest that dextral shearing has occurred along many of the major faults. The main regional fault trend is approximately north-south, but north of the Río Cinto lineament (see section 5.4) there is a swing towards north-northeast. North of the Río Pilatón the Toachi-Toacazo Fault has an exceptional north-northwest trend. Approximately east-west trending minor faults are interpreted from displacements of the Apagua, Unacota and Pallatanga units in the areas north of Sigchos, east of Pilaló and south of Calacalí respectively, but faults of this trend are of very local occurrence only.

A complex array of approximately north-south trending faults marks the eastern limit of the Cretaceous and Tertiary sequences of the cordillera and their contact with the thick Quaternary volcanic deposits of the inter-Andean graben. Field evidence for these faults is sparse because for the most part they are concealed beneath very thick Quaternary deposits, and their interpretations are based mainly on regional considerations. The easternmost of these is the eastern bounding fault of the Cretaceous and Tertiary sequences of the Western Cordillera, which is interpreted to be the southern extension of the Cauca-Patía Fault of Colombia (see, for example, Litherland and Aspden, 1992). This is a long-lived structure with a complex history, but in the present area its most recent phase of activity involved mainly downthrow to the east, allowing the preservation of thick Quaternary deposits in the inter-Andean graben.

At least three splay faults are associated with the main eastern bounding fault in the area between Pujilí and Saquisilí. There is evidence for the presence of these in the quebradas which drain eastwards from the cordillera, where turbidites of the Yunguilla Unit contain abundant evidence of brittle deformation in the form of quartz and calcite veins, closely spaced intense fracturing, and slickensides (e.g. in Quebrada Maca Grande [755-9904], Quebrada Quila [755-9906], Quebrada Pusuchisi [703-9907].

Another complex array of fault splays related to the main eastern bounding fault is believed to be present between a point west of Alóag and the equator. This set of faults is invoked to explain the presence within the Yunguilla Unit west and south of Calacalí [e.g. 7707-00010] of a slice of basaltic pillow lavas and related sediments of the Pallatanga Unit, and the presence within the Yunguilla Unit along the Quito-Chiriboga road of the San Juan Peridotites.

The inlier of Pallatanga Unit and Apagua Formation at Guayrapungu [743-9902] is believed to indicate the position of a regional, north-south trending fault, the Guayrapungu Fault, otherwise concealed beneath the Zumbagua Group. Kinematic indicators within the Apagua Formation here [7434-99035] show dextral movement.

The Toachi-Toacazo Fault is a very important regional fault (see section 8 for regional significance), and is unusual in having a north-west trend. It is exposed in the Río Pilatón at [7314-99649], where it consists of a narrow zone of ductile deformation with several component splays. In the Río Toachi at La Unión del Toachi [7283-99656], there is a zone of faulting which consists of at least five, closely spaced shear bands, some of which have dextral S-C fabrics. This zone is thought to be a splay of the main Toachi-Toacazo Fault, but lithological continuity across the fault zone suggests that displacement is small. Regional evidence for the existence of the Toachi-Toacazo Fault is also compelling. The successions on either side of the fault are of totally different facies and ages. On the south-west side of the fault the major components are the Macuchi Unit and the Angamarca Group, of Palaeocene to Late Eocene age, and the Zumbagua Group of Miocene age. On the north-east side of the fault the main components are the Yunguilla, Silante, Pilatón and Mulaute units, of probable Maastrichtian (or older) to early Tertiary age (the age of the Mulaute Unit is unproven).

The contact between the Silante Unit and the Pilatón Unit is not exposed, but is interpreted as a fault because of the very different ages of the two units (post-Maastrichtian and Senonian respectively; see sections 3.5 and 3.8 for further details). Similarly, the contact between the Pilatón and Mulaute units is not exposed but is tentatively interpreted as a fault. The contact between the Macuchi Unit and the Angamarca Group is also unexposed but is interpreted as a fault because it truncates the outcrop patterns of the various units of the Angamarca Group, and because the eastward younging Palaeocene to Eocene sequence on the eastern side of the contact is older than the ?Lower Eocene sequence on the western side.

5.2 The Río Mulaute shear zone

North of the Alóag-Santo Domingo road the Toachi-Toacazo Fault is the probable western limit of a dextral shear zone, best exposed in the ríos Mulaute and Macas. It is not known, because of poor exposure, if the eastern limit of the zone is also a fault. This approximately north-south trending shear zone is at least 12 km wide, and evidence of shearing can be seen from the north of Dos Ríos in the east where a diorite intrusion is strongly foliated [7340-99698] to the suspension bridge over the Río Mulaute at Diez de Agosto [7224-99882] in the west.

The age of the shearing event is unproven. However, the diorite intrusion mentioned above (and another further north) contains amphibole aggregates comprising hornblende cores and actinolite overgrowths (see section 4.3). K-Ar analysis of a hornblende mineral separate from this rock gave an age of 48.28 ± 0.55 Ma (Early to Mid Eocene). This age is almost certainly reset, and probably represents the age of the deformation event.

The shear zone consists of a broad are of penetrative cleavage development, within which there are at least two zones of ductile deformation. Cleavage is extremely well developed in the dark grey mudstones and siltstones of the Mulaute Unit, for example at Puerto Nuevo [7244-99881], Diez de Agosto [7224-99882] and in a quarry in the valley of the Río Macas [7279-99956]. It normally has an approximately north-south trend and is moderately to steeply dipping (45-80°) to the east and west. Gently plunging stretching lineations (up to 35°) indicative of strike-slip movement are commonly visible on S_1 planes (for example at Puerto Nuevo and Diez de Agosto). Zones of ductile deformation are visible in the Río Mulaute at [7293-99799] (thin section RH-339) where the sense of movement is indeterminate, and in the Río Macas at [99261-7890] (thin section RH-325) and [7270-99925], where S-C mylonite fabrics indicate dextral movement. (Note that dextral S-C mylonites are also present in the fault zone at La Unión del Toachi [7278-99654]; this fault zone is interpreted to be a splay fault of the main Toachi-Toacazo fault structure).

5.3 Folding

Folding is present within the Silante and Pilatón units on the north-eastern side of the Toachi-Toacazo fault. North-south trending, large-scale, tight anticlines and synclines with apparently upright fold axial planes are present within the Silante Unit along the Alóag-Santo Domingo road between Cerro Tatatambo [755-9951] and San Ignacio [749-9950], and along the old Quito-Santo Domingo road east of Guarumal [754-9969]. North-south trending, minor, open folds are present within the Pilatón Unit along the Alóag-Santo Domingo road at, for example, La Esperie [7273-99955]. No cleavage development has been observed around the folds within the Pilatón and Silante units.

On the south-western side of the Toachi-Toacazo fault the Macuchi Unit and Zumbagua Group are folded. Approximately north-south trending, large scale, gentle to open synclines and anticlines are present in the Zumbagua Group on the high páramo between Zumbagua, Pujilí and Sigchos (see Plate 7b), and are readily visible on aerial photographs. Northeast-southwest trending, large and small scale, close to tight anticlines and synclines are present within the Macuchi Unit in the area surrounding Comuna Monte Nuevo [709-9940]; these too are visible on aerial photographs. The northeast-southwest trend of these fold axes is conspicuously different from all other known fold axes in the area, and may imply an element of rotational movement on the Toachi-Toacazo Fault.

The age of the folding is poorly constrained. That which affects the Zumbagua Group is Late Miocene or younger (see section 3.12.2 for evidence of the age of the Zumbagua Group), but it is possible that the folding which affects the Macuchi, Silante and Pilatón units is older.

5.4 Lineaments

Photolineaments, visible on aerial photographs and/or Landsat images, are common and are mainly related to bedding features. A set of very conspicuous north-east trending bedding-related lineaments is present, for example, within the Macuchi Unit between Santa María del Toachi [797-9929] and Cooperativa de Trabajadores Libres [714-9954].

Extensive lineaments which are not related to bedding are uncommon. The north-south trending Río Toachi lineament forms a very conspicuous feature south of the Sigchos area, and its southern extension is the Río Chimbo Lineament (McCourt et al., 1997). The Río Toachi lineament is probably a neotectonic structure which reactivates a basement fault, and it may explain the position of the Quilotoa volcano. The lineaments of the valleys of the Río Cinto [e.g. 7754-9980] on the south side of the Pichincha massif, and the Río Pilatón between La Esperie [739-9961] and San Ignacio [749-9950] are said to be neotectonic fractures (Iglesias et al., 1992), but there is no obvious field evidence of fracturing or displacement.

6. MINERALISATION

In comparison with other parts of the Western Cordillera, there is relatively little mining activity and known mineralisation between 0°00' and 1°00'S. Placer gold is currently worked at Estero Hondo [796-9893] by Odin Mining International Inc. at La Maná. It is known that there is more than one primary gold source here, and that one source is a product of skarn mineralisation (Dr. Mike Potter, pers. comm.). A small-scale, artisanal gold-panning operation is present in Estero Daule [7090-99045], some 17 km northeast of Estero Hondo, where small river terraces contain detrital gold which may be of skarn origin.

At the time of the survey there was considerable exploratory activity including an extensive drilling programme at the Macuchi mine [716-9997], a site where production of gold, silver and copper has occurred intermittently since the 1940s. According to site geologists there are at least three, north-south aligned, steeply inclined ore-bodies, in which the intensity of mineralisation is said to increase with depth. It appears that the mineralisation is hosted almost entirely by sedimentary rocks. In some breccia beds only the clasts are mineralised, suggesting very early mineralisation processes. The facies assemblage present at Macuchi (and possibly at La Plata) is strongly suggestive of submarine exhalative mineralisation. Within the immediate vicinity of the Macuchi mine are exposures of andesitic pillow lavas and high-level intrusions, debrite breccias, hyaloclastites and volcanoclastic turbidite sandstones. Similar facies are present at numerous other sites within the area of outcrop of the Macuchi Unit.

The La Plata mine [7292-99567] north of San Francisco de Las Pampas, where copper, zinc, lead and gold have been worked, is now abandoned. The mine occurs in an area of very poor exposure, and the type of mineralisation is poorly understood, though Egüez (1986) interprets the deposit as 'Kuroko' type. Exposures of dioritic intrusives with disseminated pyrite and in veins, chalcopyrite and sphalerite are present in the area of the disused workings.

In addition to these sites of major economic mineralisation Paladines and Rosero (1996) report mineralisation from the following localities within the present area: Isinliví (Ag), Palmar (3 km east of Macuchi, Au), Pilaló (Au), Sigchos (Ag, Cu), Tenefuerte (Au), Zarapullo (Ag), Río Pilatón (Au) and Mindo (Au). During survey activities we received verbal reports of alluvial gold at unspecified localities in the Nono area, north-west of Quito, and in the Río Victoria upstream from Comuna Monte Nuevo [711-9942]. This information indicates that although mineralisation is most abundant within the Macuchi Unit, it is not confined to that unit.

7. NON-METALLIC MINERALS

Non-metallic minerals are worked throughout the area, but only to supply local demand. Of the numerous works the following are the most important. Limestone (within the Macuchi Unit, see section 3.9.3.3) is worked locally at Tenefuerte east of La Maná, and is used for cement making and reputedly for ornamental stone. The Unacota Formation (section 3.11.2) was formerly worked by Cementos Cotopaxi at Cerro Unacota, but these quarries are now inactive. Alluvial sands and gravels of the Río Toachi and Río San Pablo are worked in the Santo Domingo and La Maná areas respectively, to supply the demands of the local construction industry. Quaternary ashes are worked around Pujilí and Saquisilí for bricks and ceramics.

8. GEODYNAMIC MODEL

Many important aspects of the model presented below depend on the interpretation of the little-known area of the Western Cordillera between 0° and the Ecuador-Colombia border. This area is due to be surveyed in 1997-1999, and the findings of the survey may demand modification of the model.

Regional considerations suggest that two 'terranes' may be present within the present area, separated by the Toachi-Toacazo Fault (see section 5.1 for details). To the north-east of the fault the sequence consists mainly of the Yunguilla, Silante, Pilatón and Mulaute units, of probable Maastrichtian (or older) and post-Maastrichtian age. To the south-west of the fault the sequence consists of the Macuchi Unit and the Angamarca Group, both of Mid Palaeocene or younger age. Kinematic indicators along the fault structure suggest a dextral shear regime.

It is suggested that the southern extension of the Toachi-Toacazo Fault structure is the approximately north-south trending Pallatanga Fault system, which at Pallatanga swings to the south-west and leaves the cordillera, entering the Pacific Ocean south of the Gulf of Guayaquil in the region of the Jambelí Fault. The northern extension of the Toachi-Toacazo Fault is as yet unknown. Therefore, considering the cordillera as a whole, it appears that rocks of the Macuchi and the Angamarca Group are restricted to the west of the Toachi-Pallatanga Fault system.

If the model is correct, when were the terranes accreted? There is very little direct evidence for the age of accretion of the older terrane. Aspden et al. (1992) proposed that widespread resetting of isotopic ages in the Cordillera Real of Ecuador at 85-65 Ma was caused by uplift resulting from the earliest stages of accretion of the Western Cordillera. This is supported by evidence of the deposition of very different sedimentary facies in Maastrichtian times on either side of the Cordillera Real, with marine turbidites of the Yunguilla Unit to the west, and the red-beds of the Tena Formation to the east, implying emergence of the proto-cordillera prior to or by the Maastrichtian (Baldock and Longo, 1982).

In the present area, the Silante Unit is a very thick, autochthonous sequence of terrestrial deposits (see section 3.8 for details) which must have been deposited on accreted crust of the Western Cordillera. Unfortunately, its age is poorly constrained, but to the north-west of Quito it overlies (with possible non-sequence) the Maastrichtian marine turbidites of the Yunguilla Unit; its age can be said with certainty only to be post-Maastrichtian (see section 3.7 and 3.8). The change in depositional environment at the Yunguilla-Silante contact clearly reflects an important regional uplift event.

Assuming the Silante Unit is indeed autochthonous, then the accretion event in the cordillera was completed during (or in pre-) Maastrichtian times. The regional uplift event which affected the Yunguilla Unit was probably directly related to this accretion event. The Pallatanga Unit and San Juan Peridotites are interpreted to be oceanic fragments, accreted in Maastrichtian or earlier times, during the same event which produced the Pujilí Unit. The probably Senonian and younger Mulaute and Pilatón volcanosedimentary units were deposited upon the same oceanic crust, and were accreted during the same event. The Yunguilla Unit is believed to be the marine turbidite system which developed in the fore-arc region, derived from the Cordillera Real. This interpretation is supported by the petrography of the Yunguilla sandstones, which contain metamorphic and some fresh, subaerial volcanic input (see section 3.7.3).

The probable age of accretion of the younger ('Macuchi-Apagua') terrane is better constrained. The Macuchi Unit and the Angamarca Group, of Early to Mid Palaeocene to Late Eocene age (see sections 3.9 and 3.11 for details), are generally moderately to steeply dipping, and are unconformably overlain by the gently dipping Zumbagua Group, of Miocene age (see section 3.12 for details). This evidence indicates a major tectonic event in post-Late Eocene to pre-Miocene times. Furthermore, the Macuchi Unit is intruded by numerous I-type granitoid plutons, the oldest of which (from the Río Hugshatambo, Pucayacu – see section 4.1 for details) has a K-Ar hornblende age of 38.09 ± 0.39 Ma. This evidence suggests that accretion of the Macuchi Unit island-arc sequence and the fore-arc or marginal basin sedimentary sequence of the Angamarca Group had taken place by latest Eocene times. The reset K-Ar hornblende age of 48 Ma from a foliated diorite intrusion in the Río Mulaute shear zone (see sections 5.1 and 5.2) might indicate that the first stages of this accretionary event began in Mid Eocene or earlier times.

The two accretionary events were followed during Miocene times by probable inter-montane basin deposition, from an andesitic volcanic source, of the Zumbagua Group.

In summary, the likely sequence of events began with the accretion of the Pallatanga, San Juan, Pujilí, Pilatón and Mulaute units in approximately Maastrichtian times. This accretionary event produced uplift of the continental margin and its fringing turbidite fan deposits (Yunguilla Unit), producing a continental environment in which an andesitic volcanic arc supplied material to the Silante Unit. The Macuchi Unit and the Angamarca Group represent an island arc and marginal basin or fore-arc sedimentary sequences, probably accreted in Late Eocene times along the Toachi-Toacazo Fault in a dextral shear regime. During the Miocene the accreted allochthon of the cordillera was the site of extensive andesitic volcanism, the products of which in the present area are the volcanosedimentary rocks of the Zumbagua Group.

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10. BIBLIOGRAPHY

AGUIRRE L. and ATHERTON M. P. (1987) Low grade metamorphism and geotectonic setting of the Macuchi Formation, Western Cordillera of Ecuador. *Journal of Metamorphic Geology,* **5**, 473-494.

ASPDEN J. A., BONILLA W. and DUQUE P. (1992) New geochronological control for the tectono-magmatic evolution of the metamorphic basement, Cordillera Real and El Oro Province of Ecuador. *Journal of South American Earth Sciences, 6, 77-96.*

ASPDEN J. A., BONILLA W. and DUQUE P. (1995) The El Oro metamorphic complex, Ecuador: geology and economic mineral deposits. *Overseas Geology and Mineral Resources,* No. 67, 63 pp.

BALDOCK J. W. (1982) Geología del Ecuador. Boletín de la Explicación del Mapa Geológico (1:1000000) de la República del Ecuador. Ministerio de Recursos Naturales y Energéticos. Quito, 54 pp.

BALDOCK J. W. and R. LONGO (1982) Mapa Geológico Nacional de la República del Ecuador. MRNE-IGS. Quito.

BRISTOW C. R. (1981) An annotated bibliography of Ecuadorian geology. *Overseas Geology and Mineral Resources, Institute of Geological Sciences,* No. 58, 38 pp.

BRISTOW C. R. and HOFFSTETTER R. (1977) *Lexique Stratigraphique International.* (2nd Edition). Centre National de la Recherche Scientifique, Paris.

BRUET F. (1987) Los xenolitos en las lavas de los volcanes de Quito, República del Ecuador. Politécnica, Quito, XII, No. 2, 113-128.

CEREZO E., EGÜEZ A., SERRANO C. and F. VILLALBA (1979) Rocas básicas y ultrabásica de la Región de Saloya. Escuela Politécnica Nacional, Facultad de Geología, Minería y Petróleo. Unpublished report.

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1976) Mapa geológico del Ecuador, Machachi, Hoja 66 (1:100000). (Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1978) Mapa geológico del Ecuador, Valencia, Hoja 47 (1:100000). (Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1979) Mapa geológico del Ecuador, Las Delicias, Hoja 46 (1:100000). (Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1979) Mapa geológico del Ecuador, Quito, Hoja 65 (1:100000). (Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1979) Mapa geológico del Ecuador, Latacunga, Hoja 67 (1:100000). (Quito).

ECHEVERRÍA M. (1977) Geología del cuerpo calcáreo de Unacota, Pilaló-Cotopaxi. Tesis ingeniero, Escuela Politécnica Nacional, Quito (inédito), 123 p.

EGÜEZ A. (1986) Evolution Cénozoïque de la Cordillère Occidental Septentrionale d'Equateur (0°15'S o 1°10'S). Les mineralisation associées. Unpublished Ph. D. thésis, Université Pierre et Marie Curie, Paris, 116p.

EGÜEZ A. y BOURGOIS J. (1986) La Formación Apagua, edad y posición estructural en la Cordillera Occidental del Ecuador. Memoria Cuarto Congreso Ecuatoriano de Geología, Minas y Petróleos, **Tomo 1**, 161-178. Quito.

FAUCHER B., JOYES R., MAGNE F., GRANJA V. J., GRANJA B. J. C., CASTRO R. y GUEVARA G. (1968) Informe geológico sobre las posibilidades petroleras de las provincias costeras de la República del Ecuador. Institute Français du Pétrole. (Servicio Nacional de Geología y Minas; Quito).

FAUCHER B., VERNET R., BIZON G., BIZON J. J., GREKOFF N., LYS M. and SIGAL J. (1971) Sedimentary formations in Ecuador. A stratigraphic and micropaleontological Survey. (Bureau d'etudes industrielles et de cooperation del Institut Français du Petrole (BEICIP)). Paris.

FAUCHER B. and SAVOYAT E. (1973) Esquema Geológico de los Andes Ecuatorianos. *Revue de géographie et de Géologie Dynamique (2),* **XV Fase 1-2**, 115-142. Paris.

FEININGER T. (1977) Simple Bouguer gravity anomaly map of Ecuador (1:1000000). Escuela Politécnica Nacional, Quito, Ecuador.

FEININGER T. (1978) Geologic map of the western part of the El Oro Province (1:50000). Escuela Politécnica Nacional, Quito, Ecuador.

FEININGER T. and BRISTOW C. R. (1980) Cretaceous and Paleogene geologic history of coastal Ecuador. *Geologische Rundschau,* Vol. 69, 849-874.

GANSSER A. (1973) Facts and theories on the Andes. Journal of the Geological Society of London, Vol. 129, 93-131.

GOOSSENS P. J. (1972) Los Yacimientos e indicios minerales metálicos y no metálicos de la República del Ecuador. Depto. de Geología, Universidad de Guayaquil, Ecuador.

GOOSSENS P. J. and ROSE W. I. (1973) Chemical composition and age determination of tholeiitic rocks in the Basic Igneous Complex, Ecuador. *Bulleting Geological Society of America*. **84**, 1043-1052.

HALL M. L. and MOTHES P. A. (1994) Tefroestratigrafía holocénica de los volcanes principales del valle interandino, Ecuador. P. 47-68. *In* El Contexto Geológico del Espacio Físico Ecuatoriano (ed. R. Marocco). Colegio de Geógrafos del Ecuador, Quito-Ecuador, 113 p.

HENDERSON W. G. (1977) Geology of the Cordillera Occidental of Northern Ecuador. Internal report IGS/DGGM Quito 79p.

HENDERSON W. G. (1979) Cretaceous to Eocene volcanic arc activity in the Andes of northern Ecuador. *Journal of the Geological Society of London*, Vol. 136, 367-378.

HENDERSON W. G. (1981) The Volcanic Macuchi Formation, Andes of Northern Ecuador. *Newsl. Stratigr.,* **9**, 157-168.

IGLESIAS R., EGÜEZ A. and PÉREZ V. H. (1992) Mapa Sismotectónico del Ecuador. Consejo de Seguridad Nacional, Dirección Nacional de Defensa Civil, Quito, Ecuador.

INEMIN (1986) Hoja geológica de Santo Domingo (45), escala 1:100000, Quito.

IRVINE T. N. and BARAGAR W. R. A. (1971) A guide to the chemical classification of the common volcanic rocks. *American Journal of Earth Sciences,* **8**, 523-548.

the mineral exploration in the Bolívar area, Republic of Ecuador, Phase III, CODIGEM, Quito.

JUTEAU T., MEGARD F., RAHARISON L. and WHITECHURCH H. (1977) Les assemblages ophiolitiques de l’occident equatorien : nature pétrographique et position structurale. *Bulletin Societe Geologique de France,* **19**, 1127-1132.

KENNERLEY J. B. (1980) Outline of the geology of Ecuador. Institute of Geological Sciences. *Overseas Geology and Mineral Resources,* No. 55, 20 pp.

KEHRER W. and VAN DER KAADEN G. (1979) Notes on the geology of Ecuador, with special reference to the Western Cordillera. *Geol. Jahrbuch,* **35**, 5-57.

LE MAITRE R. W. (1989) A Classification of Igneous Rocks and glossary of terms. Blackwell. London.

LEBRAT M. (1985) Caractérisation géochimique du volcanisme anté-orogénique de l’Occident Equatorien : implications géodynamiques. Unpubl. Ph. D. Thesis. Centre Geologique et Geophysique de Montpellier. 119p.

LEBRAT M., MEGARD F., JUTEAU T. and CALLE J. (1985) Pre-orogenic volcanic assemblage and structure in the Western Cordillera of Ecuador, between 1°40’S and 2°20’S. *Geologische Rundschau,* **74**, 343-351.

LEBRAT M., MEGARD F., DUPUY C. and DOSTAL J. (1987) Geochemistry and tectonic setting of pre-collision Cretaceous and Paleogene volcanic rocks of Ecuador. *Bulletin of the Geological Society of America,* **99**, 569-578.

LITHERLAND M. and ASPDEN J. A. (1992) Terrane-boundary reactivation: a control on the evolution of the Northern Andes. *Journal of South American Earth Sciences,* **5**, 71-76.

LITHERLAND M., ZAMORA A. and A. EGÜEZ (1993a) National Geological Map of Ecuador, Scale 1:1000000 (Keyworth, Nottingham: British Geological Survey and Quito: CODIGEM).

LITHERLAND M., ZAMORA A. and A. EGÜEZ (1993b) National Metallogenic Map of Ecuador, Scale 1:1000000 (Keyworth, Nottingham: British Geological Survey and Quito: CODIGEM).

LITHERLAND M., ASPDEN J. A. and JEMIELITA R. A. (1994) The metamorphic belts of Ecuador. Overseas Memoir 11. Keyworth: British Geological Survey.

LONSDALE P. (1978) Ecuadorian Subduction System. *Bulletin American Association of Petroleum Geologists,* **62**, 2454-2477.

McCOURT W. J., ASPDEN J. A. and BROOK M. (1984) New geological and geochronological data from the Colombian Andes: Continental growth by multiple accretion. *Journal of the Geological Society of London,* **141**, 831-845.

McCOURT W. J., DUQUE P. and PILATASIG L. (1997) Proyecto de Desarrollo Minero y Control Ambiental, Programa de Información Cartográfica y Geológica. Report No. 3. Geology of the Western Cordillera of Ecuador between 1°00'S and 2°00'S.

MESCHEDE M. (1986) A Method of discriminating different types of mid-ocean ridge basalt and continental tholeiites with the Nb-Zr-Y diagram. Cem. Geol., **56**, 207-218.

MEGARD F. and LEBRAT M. (1987) Los terrenos exóticos del occidente Ecuatoriano y sus relaciones con Sudamérica. Coloquio Ecuador 86, Quito, *Casa Cultura*, **240**, 161-172.

OLSSON A. A. (1942) Tertiary deposits of north-western South America and Panamá. *Proceedings of the American Scientific Congress.* Washington, 231-287.

PALADINES A. and ROSERO G. (1996) Zonificación mineralógica del Ecuador. Quito.

PEARCE J. A. (1975) Basalt geochemistry used to investigate past tectonic environments on Cyprus. *Tectonophysics*, **25**, 41-77.

PEARCE J. A. and NORRY M. J. (1979) Petrogenic implications of Ti, Zr, Y and Nb variations in volcanic rocks. *Contributions to Mineralogy and Petrology*, **69**, 33-47.

REA D. K. and MALFAIT B. T. (1974) Geologic evolution of the Northern Nazca Plate. *Geology*, **2**, 317-320.

READING H. G. (1986) Sedimentary Environments and facies. (2nd Edition). Blackwell Scientific Publication, London, 615 p.

SANTOS M. and RAMÍREZ F. (1986) La Formación Apagua, una nueva unidad eocénica en la Cordillera Occidental ecuatoriana. *Memorias Cuarto Congreso Ecuatoriano de Geología, Minas y Petróleos*, **Tomo 1**, 179-189.

SAUER W. (1957) *El mapa geológico del Ecuador. Memoria explicativa.* (Universidad Central; Quito).

SAUER W. (1965) *Geología del Ecuador.* Edit. Ministerio de Educación Pública. Quito, 383 p. (Quito).

SAVOYAT E., VERNET R., SIGAL J., MOSQUERA C., GRANJA J. and GUEVARA G. (1970) Formaciones sedimentarias de la Sierra tectónica andina en el Ecuador. Informe Instituto Francés del Petróleo y Servicio Nacional de Geología y Minería, Quito.

SERVICIO NACIONAL DE GEOLOGÍA Y MINERÍA (1969) Mapa geológico de la República del Ecuador. (1:1000000). (Quito).

SHERVAIS J. W. (1982) Ti vs. V plots and the petrogenesis of modern and ophiolitic lavas. *Earth and Planetary Science Letters*, **59**, 101-118.

SIGAL J. (1968) Estratigrafía micropaleontológica del Ecuador, datos anteriores y nuevos. Informe Instituto Francés del Petróleo y Servicio Nacional de Geología y Minería, Quito.

SILLITOE R. H. (1974) Tectonic segmentation of the Andes: implication for magmatism and metallogeny. Nature, London, Vol. 250.

STEINMANN M. (1977) Fission-track age determinations on Zircons. Consultants Report, GIMP mapping project Ecuador, Geological Institute **ETH,** Zürich, Switzerland, 59p.

THALMANN H. E. (1946) Micropalaeontology of Upper Cretaceous and Paleocene in Western Ecuador. *Bulletin of the American Association of Petroleum Geologists*, **30**, 337-347.

TSCHOPP H. J. (1948) Geologische Skizze von Ekuador. *Bull. Assoc. Suisse Géol. Ing. Pét.*, Vol. 15, 14-45.

TSCHOPP H. J. (1953) Oil explorations in the Oriente of Ecuador. 1938-1950. *Bulletin of the American Association of Petroleum Geologists,* Vol. 37, 2303-2347.

VAN THOURNOUT F. (1991) Stratigraphy, magmatism and tectonism in the Ecuadorian Northwestern Cordillera: metallogenic and geodynamic implications. Unpublished PhD. Thesis Katholieke Universiteit Leuven.

VAN THOURNOUT F., HERTOGEN J. and QUEVEDO L. (1992) Allochthonous terranes in northern Ecuador. *In:* Andean Geodynamics, Special Volume, *Tectonophysics*, **205**, 205-222.

WALLRABE-ADAMS H. J. (1991) Petrology and Geotectonic development of the Western Ecuadorian Andes: the Basic Igneous Complex. *Tectonophysics*, **185**, 163-182.

WHYMPER E. (1892) Travels amongst the Great Andes of The Equator. (London: Murray).

WILKINSON I. P. (1997) Foraminifera from a suite of samples from Ecuador. Technical Report WH/97/85R, Biostratigraphy and Sedimentology Research Group BGS Nottingham UK.

WOOD D. A. (1980) The application of a Th-Hf-Ta diagram to problems of tectonic magmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. *Earth and Planetary Scientific Letters*, **50**, 11-30.

WOLF T. (1892) Geografía y Geología del Ecuador. Brockhaus, Leipzig.

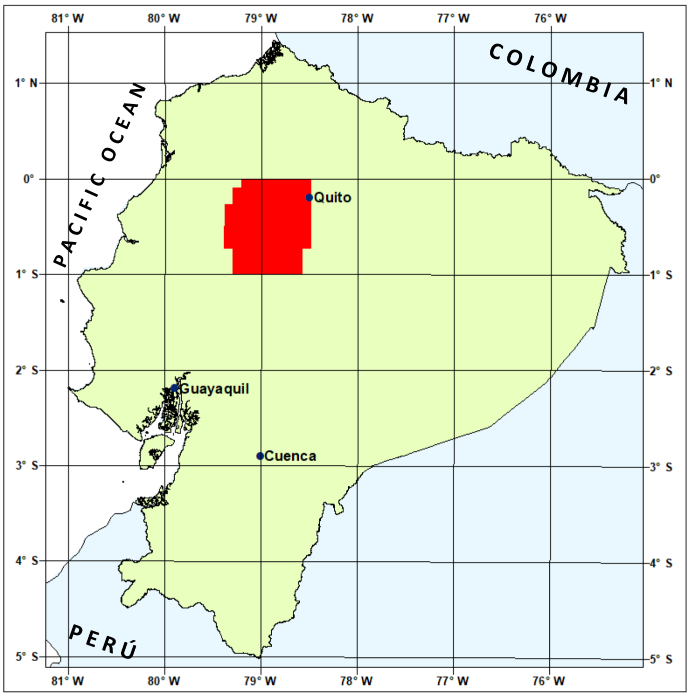
APPENDIX 1 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA

OF ECUADOR

BETWEEN 0°00’ AND 1°00’ S

GEOCHEMICAL DATA



GEOLOGICAL INFORMATION MAPPING PROGRAMME

(LOCATION OF MAP 4 AREA)

QUITO, 1997

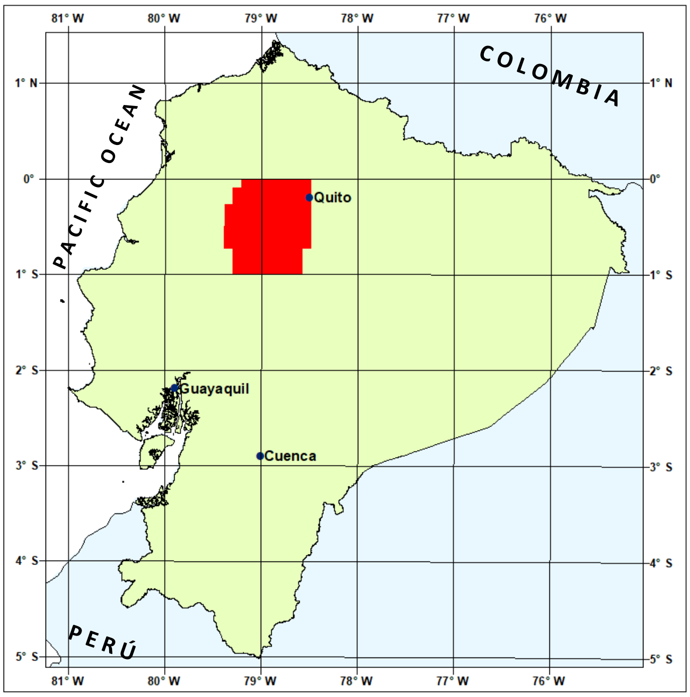
SAMPLE	**RH-5**	**RH-122A**	**RH-122B**	**RH-130A**	**RH-258A**	**RH-258B**	**RH-258C**	**RH-274**	**RH-276**	**RH-278B**
UTMX	7164	7171	7171	7305	7096	7096	7096	6886	7200	7249
UTMY	99024	99675	99675	99657	99432	99432	99432	99314	99685	99654
UNIT	Macuchi	Macuchi	Macuchi	Macuchi	Macuchi	Macuchi	Macuchi	Macuchi	Macuchi	Macuchi
LOCALITY	Macuchi	Río Toachi	Río Toachi	Río Pilatón	Monte Nuevo	Monte Nuevo	Monte Nuevo	Patricia Pilar	Río Toachi	Río Toachi
SiO_2	60.17	61.90	59.61	62.77	57.13	56.13	57.26	53.87	48.97	48.74
TiO_2	0.48	0.47	0.39	0.87	0.59	0.57	0.63	0.66	0.67	0.74
Al_2O_3	11.76	11.59	12.26	14.85	15.96	15.22	15.42	15.75	15.57	17.73
Fe_2O_3	6.38	7.46	7.42	7.51	6.96	6.95	8.16	9.53	8.31	7.91
MnO	0.20	0.20	0.24	0.17	0.17	0.17	0.21	0.17	0.20	0.17
MgO	2.50	3.67	5.30	3.75	4.58	5.41	6.24	3.78	7.05	8.45
CaO	11.47	8.23	9.48	1.86	6.32	6.42	5.47	7.91	9.99	9.00
Na_2O	3.60	4.26	4.01	4.39	3.47	4.32	3.31	2.75	3.79	2.38
K_2O	0.11	0.05	0.10	1.08	1.64	0.50	1.03	0.67	0.08	1.32
P_2O_5	0.12	0.10	0.12	0.24	0.18	0.19	0.19	0.10	0.12	0.14
LOI	3.37	1.73	1.02	2.70	2.63	3.98	2.28	4.47	4.91	3.38
Total	**100.16**	**99.66**	**99.95**	**100.19**	**99.63**	**99.86**	**100.20**	**99.66**	**99.66**	**99.96**
Ba	50	25	36	591	313	108	200	455	53	119
Ce	16	0	9	12	0	12	16	15	8	15
Co	21	34	32	18	22	26	28	38	37	38
Cr	17	19	31	17	49	35	85	27	286	213
Cs	1	0	1	1	1	0	0	0	1	0
Hf	0	6	4	0	0	0	8	4	6	6
La	0	6	0	15	10	5	13	7	0	8
Nb	4	3	2	3	2	3	3	2	2	3
Nd	11	5	5	18	12	7	13	13	3	11
Ni	11	11	14	5	19	23	40	21	200	132
Rb	0	0	0	8	26	8	15	29	0	43
Sc	28	37	28	25	30	25	27	32	34	34
Sm	15	7	0	7	7	2	6	11	5	5
Sr	97	86	131	121	156	94	157	397	138	322
Ta	0	0	0	0	0	0	0	0	0	0
Th	2	1	2	2	1	3	2	1	1	2
U	2	2	0	3	3	2	2	1	3	0
V	199	232	189	127	233	225	260	261	232	217
Y	15	12	12	36	20	17	20	20	18	19
Zr	43	33	26	107	53	40	54	53	54	71

SAMPLE	RH-279B	RH-280B	RH-282B	RH-297	RH-299	RH-84	RH-343	RH-344	RH-351
UTMX	7261	7277	7219	7313	7219	7515	7196	7106	7338
UTMY	99655	99653	99650	99439	99428	98938	99169	99195	99941
UNIT	Macuchi	Macuchi	Macuchi	Macuchi	Macuchi	-	-	-	-
LOCALITY	Río Toachi	Río Toachi	Río Toachi	Río Toachi	Río Toachi	Pujilí	Río Quindigua	Hugshatambo	Zumbagua
SiO_2	51.14	54.65	52.52	52.69	62.58	56.33	66.07	51.86	64.38
TiO_2	0.69	0.52	0.63	0.73	0.80	0.87	0.48	0.76	0.52
Al_2O_3	15.42	14.34	15.96	16.65	13.19	17.74	15.67	17.67	17.13
Fe_2O_3	8.46	7.28	8.07	12.10	9.18	6.53	4.67	9.61	5.13
MnO	0.16	0.19	0.15	0.13	0.09	0.07	0.09	0.19	0.08
MgO	11.00	10.29	7.60	4.54	6.19	2.44	1.93	5.38	2.32
CaO	7.42	5.26	8.40	5.89	1.08	7.73	4.52	10.74	5.06
Na_2O	1.90	3.12	3.63	3.94	2.77	3.07	3.81	2.18	3.95
K_2O	0.50	0.04	0.15	0.07	0.75	1.47	2.12	0.63	1.17
P_2O_5	0.12	0.09	0.09	0.41	0.20	0.23	0.12	0.14	0.15
LOI	2.98	4.14	2.77	2.38	3.54	3.60	0.29	0.46	0.27
Total	**99.79**	**99.92**	**99.97**	**99.53**	**100.37**	**100.08**	**99.77**	**99.62**	**100.16**
Ba	73	59	64	66	570	426	430	139	451
Ce	0	11	9	19	0	20	12	21	0
Co	41	36	37	51	26	23	12	29	11
Cr	374	374	235	339	14	79	20	30	23
Cs	0	0	1	0	0	0	0	0	0
Hf	4	0	7	14	6	0	3	6	6
La	6	0	0	13	10	15	15	0	11
Nb	3	1	3	2	3	7	5	4	2
Nd	10	7	5	12	13	16	16	14	12
Ni	243	176	149	78	7	37	13	17	10
Rb	8	0	3	0	6	33	44	8	18
Sc	39	34	32	40	28	21	15	36	13
Sm	0	17	12	0	2	0	2	10	18
Sr	231	51	105	161	60	586	290	420	540
Ta	0	0	0	0	3	0	0	0	0
Th	2	1	1	1	1	1	1	1	1
U	0	0	0	0	0	0	0	0	0
V	217	210	203	274	253	225	101	271	116
Y	20	16	16	44	22	12	17	21	9
Zr	49	42	53	55	62	108	128	60	82

APPENDIX 2 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 0°00' AND 1°00' S

GEOCHRONOLOGY



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 4 AREA)

QUITO, 1997

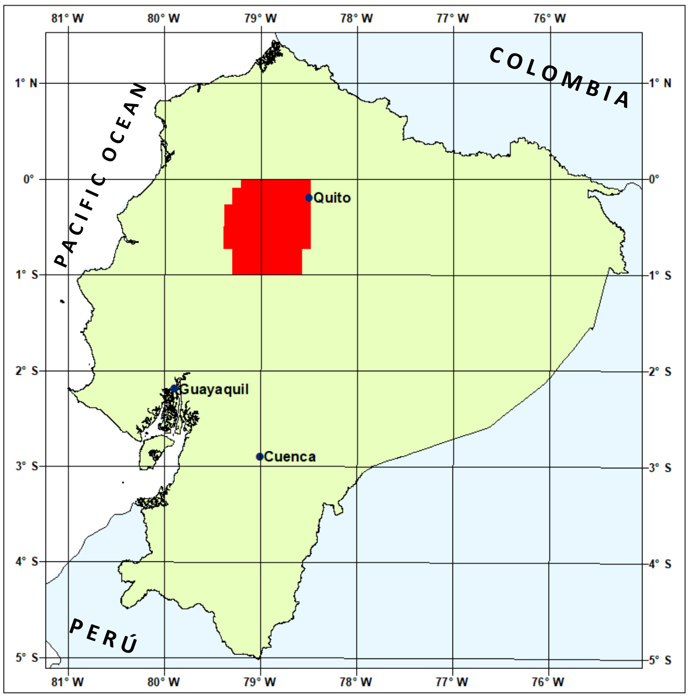
Table 1. Geochronology. K-Ar and fission track methods

Sample #	Topographic sheet	UTMX	UTMY	Method	Age (Ma)
RH-60	Pilaló	7331	98938	Fission track (zircon)	15.5 ± 1.2
RH-67	Pilaló	7351	98994	Fission track (zircon)	8.4 ± 1.2
RH-76	Pilaló	7430	99070	Fission track (zircon)	15.3 ± 1.9
RH-98	Sigchos	7425	99143	Fission track (zircon)	Not datable
RH-99	Sigchos	7432	99143	Fission track (zircon)	10.9 ± 0.9
RH-150	Alluriquín	7340	99698	K-Ar (hornblende)	48.28 ± 0.55
RH-188	Calacalí	7615	00029	Fission track (zircon)	16.8 ± 0.8
RH-270	La Maná	7203	99973	Fission track (zircon)	7.0 ± 0.3
RH-342	Sigchos	7414	99184	Fission track (zircon)	14.5 ± 2.7
RH-343	Pucayacu	7196	99169	K-Ar (biotite)	14.80 ± 0.14
RH-343	Pucayacu	7196	99169	K-Ar (hornblende)	13.31 ± 0.44
RH-344	Pilaló	7106	99195	K-Ar (hornblende)	38.09 ± 0.39
RH-351	Pilaló	7339	99942	K-Ar (hornblende)	6.27 ± 0.71

APPENDIX 3 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 0°00’ AND 1°00’ S

FOSSILS



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 4 AREA)

QUITO, 1997

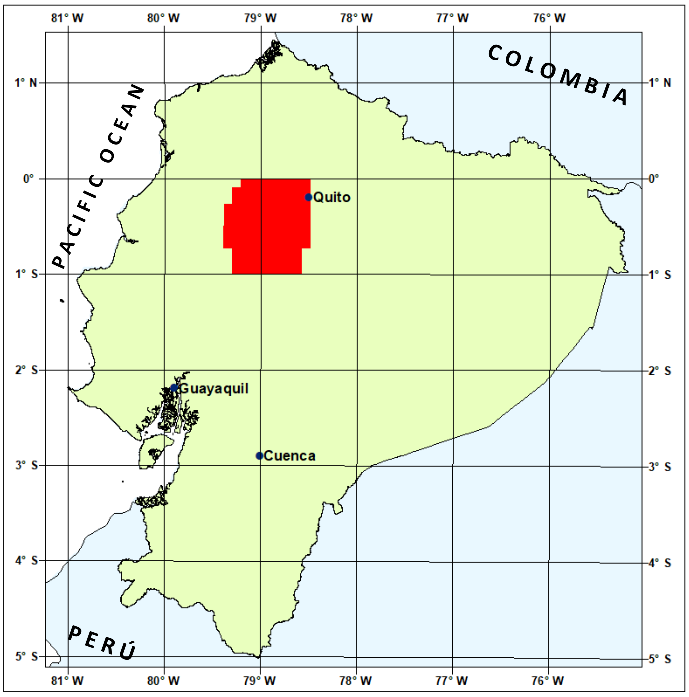
Table 1. Micropaleontological samples

Sample	Topographic sheet	UTMX	UTMY	Results
RH-60	Pilaló	7331	98938	Barren
RH-69	Pilaló	7395	98949	Barren
RH-91	Pilaló	7183	99028	Barren
RH-109A	Sigchos	7376	99248	Barren
RH-109B	Sigchos	7376	99348	Barren
RH-110	Sigchos	7404	99252	Barren
RH-191	Calacalí	7646	00036	Barren
RH-256	Alluriquín	7270	99796	Barren
RH-283A	Alluriquín	7281	99655	Barren
RH-286	Jatunloma	7272	99382	Barren
RH-291	Jatunloma	7316	99303	Barren
RH-304	Jatunloma	7234	99441	Barren
RH-310	Latacunga	7557	99006	Barren
RH-312	Latacunga	7567	99051	Barren
RH-314	Latacunga	7560	99071	Early to mid Paleocene foraminifera
RH-315	Latacunga	7556	99071	Barren
RH-316	Latacunga	7558	99062	Barren
RH-333	Mindo	7279	99956	Barren
RH-341	Cristobal Colón	7224	99882	Barren

APPENDIX 4 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 0°00’ AND 1°00’ S

PETROGRAPHY



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 4 AREA)

QUITO, 1997

Sample	UTMX	UTMY	Topographic sheet	Rock type	Description
RH-3	7142	99024	La Maná	Breccia	Fine grained, volcaniclastic breccia with abundant lithoclasts of vesicular basalt/andesite
RH-4	7152	99020	La Maná	Diabase	Plagioclase phyric, chloritised diabase
RH-6C	7164	99020	La Maná	Breccia	Poorly sorted crystal/lithic breccias with clasts of vesicular basaltic/andesitic fragments containing euhedral pyroxene and plagioclase
RH-6K	7164	99022	La Maná	Breccia	Poorly sorted crystal/lithic breccias with clasts of vesicular basaltic/andesitic fragments containing euhedral pyroxene and plagioclase
RH-6N	7164	99022	La Maná	Breccia	Fine grained crystal/lithic breccia with clasts of vesicular plagioclase-phyric andesite, some strongly porphyritic with euhedral amphiboles
RH-6P	7164	99020	La Maná	Diabase	Pyroxene-bearing diabase
RH-10	7222	98959	La Maná	Granodiorite	Granodiorite containing quartz, plagioclase (some microcline) and biotite
RH-11	7227	98958	Pilaló	Sandstone	Fine-grained, quartz-lithic, sandstone. Very well-sorted, but highly angular quartz. Mafics absent, lithics all of very fine-grained, sandstone
RH-12B & C	7232	98961	Pilaló	Sandstone	Poorly sorted, quartz-lithic sandstone. No mafics. Lithics of fine-grained igneous material. Quartz abundant, plagioclase common
RH-13	7239	98952	Pilaló	Andesite	Megaporphyritic perthitic andesite with phenocrysts of zoned plagioclase
RH-23A	7311	98924	Pilaló	Sandstone	Coarse-grained, poorly sorted quartz-lithic sandstone. No mafics. Lithics of fine-grained igneous material and rare sandstone
RH-24	7311	98899	Pilaló	Sandstone	Quartz sandstone, with rare plagioclase and biotite. Low grade thermal metamorphism evident from recrystallisation of matrix
RH-25	7140	99205	Pucayacu	Basaltic andesite	Basaltic andesite, with rare orthopyroxene
RH-27	7123	99215	Pucayacu	Andesite	Porphyritic andesite with phenocrysts of plagioclase and microcline, with highly altered? augite and pyroxene
RH-29	7184	99234	Pucayacu	Granodiorite	Granodiorite with quartz, plagioclase, microcline and biotite
RH-31	6970	98904	La Maná	Diabase	Diabase with plagioclase phenocrysts in fine-grained quartz and plagioclase matrix; some orthopyroxene
RH-34	7093	99412	Sta. María del Toachi	Sandstone	Moderately well-sorted, crystal-lithic volcaniclastic sandstone, with abundant vesicular andesitic lithoclasts
RH-35	6873	99409	Patricia Pilar	Sandstone	Poorly sorted, coarse-grained lithic sandstone containing clasts mainly of vesicular andesite
RH-36B	7058	99051	La Maná	Sandstone	Well-sorted, quartz- and plagioclase-rich sandstone
RH-37	7144	99020	La Maná	Breccia	Poorly sorted breccia with vesicular andesite and plagioclase-phyric andesite clasts. Fine-grained matrix of quartz, plagioclase and clasts
RH-38	7117	99601	San Vicente de Aquepi	Granodiorite	Coarse-grained granodiorite, with plagioclase, microcline, quartz and chlorite
RH-40	7270	98957	Pilaló	Sandstone	Poorly sorted lithic sandstone, with mainly igneous clasts of fine-grained? andesite
RH-41	7341	98935	Pilaló	Microtonalite	Porphyritic microtonalite with large phenocrysts of zoned plagioclase and hornblende
RH-45	7362	98946	Pilaló	Sandstone	Poorly sorted feldspathic (plagioclase) sandstone, with euhedral amphiboles and lithic clasts of phyric, fine-grained? andesite
RH-47	7368	98947	Pilaló	Sandstone	Crystal rich sandstone, with abundant euhedral plagioclase and hornblende, supported in very fine-grained matrix of quartz and K-feldspar
RH-52	7317	98956	Pilaló	Microtonalite	Microtonalite with small phenocrysts of zoned plagioclase and hornblende in quartz/plagioclase matrix
RH-54	7295	98973	Pilaló	Breccia	Crystal (plagioclase and rare pyroxene) and lithic rich breccia. Lithic clasts are andesitic. Matrix of fine-grained quartz and feldspar
RH-55	7286	98984	Pilaló	Sandstone/breccia	Crystal (plagioclase) lithic tuffaceous sandstone/breccia. Lithics of feldspar phyric, fine-grained igneous material
RH-60	7331	98938	Pilaló	Sandstone	Crystal rich tuffaceous sandstone – no lithics. Crystals of plagioclase, microcline, quartz and hornblende in quartz and feldspar matrix
RH-61	7334	98912	Pilaló	Tonalite	Tonalite with euhedral phenocrysts of hornblende and plagioclase (latter zoned) in quartz-plagioclase matrix
RH-65	7284	98012	Pilaló	Microtonalite	Altered microtonalite, with plagioclase and hornblende phenocrysts
RH-67	7351	98994	Pilaló	Sandstone	Crystal rich tuffaceous sandstone, with abundant plagioclase and some hornblende, in fine-grained matrix of quartz and plagioclase
RH-69	7395	98949	Pilaló	Sandstone	Very fine-grained, well sorted quartz-feldspathic sandstone
RH-70	7402	98961	Pilaló	Tonalite	Plagioclase- and microcline-phyric tonalite with small hornblendes, in matrix of fine-grained quartz and felspar
RH-72	7397	98969	Pilaló	Microtonalite	Microtonalite, with phenocrysts of quartz, plagioclase and hornblende in matrix of plagioclase and some quartz
RH-73	7405	98976	Pilaló	Siltstone	Crystal-lithic tuffaceous siltstone. Crystals mainly of zoned plagioclase, but also some hornblende and biotite. Lithics all igneous

Sample	UTMX	UTMY	Topographic sheet	Rock type	Description
RH-76	7430	99070	Pilaló	Siltstone	Crystal-lithic tuffaceous siltstone. Crystals mainly of plagioclase and quartz, with some hornblende
RH-80	7533	99009	Latacunga	Serpentinite	Foliated serpentinite
RH-83	7532	98941	Latacunga	Rhyolite	Rhyolite with phenocrysts of quartz and plagioclase in very fine-grained matrix of quartz and K-feldspar
RH-84	7515	98938	Latacunga	Basaltic andesite	Basaltic andesite with zoned plagioclase, quartz and clinopyroxene
RH-89	7161	98959	La Maná	Tonalite	Tonalite with zoned euhedral plagioclase and hornblende phenocrysts in very fine-grained matrix mainly of quartz
RH-98	7425	99143	Sigchos	Sandstone	Poorly sorted, crystal-rich sandstone with very small amounts of K-feldspar, plagioclase, biotite and abundant euhedral amphiboles
RH-101	7318	99226	Sigchos	Diorite	Coarse-grained diorite with plagioclase (zoned), quartz and orthopyroxene
RH-103	7338	99198	Sigchos	Diorite	Hornblende diorite with hornblende megacrysts in matrix of plagioclase and quartz
RH-104	7326	99172	Sigchos	Breccia	Unsorted, polymictic breccia containing exclusively fine-grained igneous clasts, some rich in K-feldspar
RH-109A	7376	99248	Sigchos	Dacite	Plagioclase and amphibole phyric dacite
RH-109B	7376	99248	Sigchos	Dacite	Plagioclase and amphibole phyric dacite
RH-109C	7376	99248	Sigchos	Dacite	Plagioclase and pyroxene phyric dacite with altered amphiboles
RH-109D	7376	99248	Sigchos	Dacite	Quartz, plagioclase and pyroxene phyric dacite with amphiboles
RH-109E	7376	99248	Sigchos	Dacite	Plagioclase, pyroxene and amphibole phyric dacite
RH-115	7542	99040	Latacunga	Hornblendite	Weakly foliated plagioclase-bearing hornblendite
RH-117	7281	99649	Alluriquín	Sandstone	Fine-grained, moderately well-sorted, silicified sandstone, with quartz, plagioclase, some euhedral pyroxenes and amphiboles
RH-121	7148	99693	Santo Domingo	Andesite	Fine-grained epidotised basaltic andesite
RH-122A	7171	99675	Santo Domingo	Breccia	Andesitic breccia with clasts of highly vesicular, very fine-grained material, and lithics with microcline phenocrysts and pyroxenes
RH-122B	7171	99675	Santo Domingo	Breccia	Andesitic breccia containing abundant vesicular clasts and lithics of very fine-grained quartz, feldspar, and pyroxene rich andesite
RH-124	7196	99659	Santo Domingo	Breccia	Andesitic breccia containing lithoclasts of highly vesicular material and lithics of plagioclase- and clinopyroxene-phyric basalt
RH-125	7243	99652	Alluriquín	Basaltic andesite	Fine-grained basaltic andesite, with plagioclase and clinopyroxene in fine-grained quartz matrix
RH-126	7240	99584	Manuel C. Astorga	Diorite	Diorite with plagioclase, quartz, and hornblende
RH-128	7282	99656	Alluriquín	Sandstone	Well sorted, fine-grained, quartz-feldspathic sandstone with plagioclase and pyroxene
RH-129	7291	99657	Alluriquín	Basaltic andesite	Fine-grained vesicular, altered, basaltic andesite
RH-132	7332	99635	Alluriquín	Tonalite	Quartz- and plagioclase-phyric tonalite? with some hornblende
RH-136	7397	99617	Manuel C. Astorga	Sandstone	Fine-grained sandstone, with abundant fine-grained vesicular material and possible shards
RH-137	7409	99609	Manuel C. Astorga	Sandstone	Fine- to medium-grained, quartz-lithic sandstone, with highly angular quartz and fine-grained vesicular lithics
RH-138A	7412	99599	Manuel C. Astorga	Sandstone	Quartz-lithic sandstone. Abundant quartz, rare altered plagioclase and pyroxene. Abundant lithoclasts of very fine-grained, vesicular material
RH-138B	7412	99599	Manuel C. Astorga	Sandstone	Highly chloritised, quartz-lithic sandstone. Angular quartz, altered feldspar and? pyroxene, with lithoclasts of fine-grained, vesicular material
RH-138C	7412	99599	Manuel C. Astorga	Sandstone	As 138B, but contains abundant vesicular material and pyroxenes
RH-138D	7412	99599	Manuel C. Astorga	Sandstone	Coarse-grained quartz-lithic sandstone. Abundant quartz, common plagioclase and rare pyroxene. Abundant vesicular lithoclasts
RH-138E	7412	99599	Manuel C. Astorga	Sandstone	As 138B, but no vesicular material, and chlorite-rich
RH-138G	7412	99599	Manuel C. Astorga	Sandstone	Poorly sorted, crystal-lithic sandstone, with abundant plagioclase and some quartz. Lithoclasts of vesicular fine-grained igneous material
RH-141	7478	99517	Manuel C. Astorga	Basaltic andesite?	Basaltic andesite? with plagioclase and pyroxene in a matrix of plagioclase and quartz
RH-143	7485	99751	Alluriquín	Sandstone	Crystal-lithic, poorly sorted sandstone. Igneous and intraformational sedimentary lithics
RH-144	7477	99740	Alluriquín	Siltstone	Highly feldspathic siltstone, with some pyroxene. Poorly sorted, angular crystals in fine grained quartz-feldspar matrix

Sample	UTMX	UTMY	Topographic sheet	Rock type	Description
RH-150	7340	99698	Alluriquín	Diorite	Foliated diorite with hornblende, actinolite, quartz and little plagioclase
RH-157	7426	99563	Tandapi	Sandstone	Well sorted, fine- to medium-grained sandstone, with pyroxenes, chlorite and some quartz
RH-163	7679	99932	Nono	Sandstone	Fine-grained, moderately well sorted quartz lithic sandstone, with rare plagioclase, microcline, biotite and muscovite
RH-169	7655	99941	Nono	Sandstone	Fine-grained sandstone with quartz and plagioclase. Rare, but excellent quartz shards
RH-178	7625	99978	Nono	Sandstone/Breccia	Lithic-rich, mafic poor, sandstone/breccia. Lithics mainly sedimentary, of quartz sandstone, with some fine-grained igneous clasts
RH-180	7619	99982	Nono	Sandstone	Crystal-lithic sandstone. Pyroxene and amphiboles present, abundant quartz and plagioclase. Sedimentary and igneous lithoclasts
RH-183	7569	99971	Nono	Sandstone	Crystal-lithic sandstone; abundant pyroxene, amphibole, plagioclase, quartz and some K-feldspar
RH-188	7615	00029	Calacalí	Sandstone	Crystal-rich, quartz sandstone, with few lithics. Amphibole very common, pyroxene less so. Rare sandstone/siltstone lithics
RH-195	7677	02121	Calacalí	Breccia	Breccia comprising igneous clasts in crystal-rich matrix. Clasts of feldspar-phyric andesites? Altered pyroxenes and amphiboles in matrix
RH-200	7685	00088	Calacalí	Sandstone	Coarse-grained, poorly sorted, plagioclase-rich crystal lithic sandstone, with some amphibole
RH-201	7686	01111	Calacalí	Sandstone	Quartz-feldspathic sandstone, with rare biotite. Serpentinised amphiboles present, some quartz aggregates are strained
RH-212B	7610	99675	Quito	Andesite	Fine-grained andesite
RH-213	7609	99676	Quito	Andesite	Fine-grained andesite
RH-215	7589	99684	Quito	Peridotite	Peridotite containing abundant pyroxene, olivine, and iddingsite?
RH-228	7556	99518	Amaguaña	Sandstone	Poorly sorted, crystal-rich, feldspathic sandstone, with plagioclase, K-feldspar, hornblende, in fine-grained matrix of plagioclase and quartz
RH-229	7553	99519	Amaguaña	Sandstone	Quartz-lithic sandstone. Lithics are mainly fine-grained sandstone, with some fine-grained igneous material. Rare amphibole
RH-230	7548	99519	Amaguaña	Sandstone-breccia	Lithic sandstone-breccia. Lithics mainly sedimentary, but some very fine-grained K-feldspar rich igneous clasts also present
RH-231	7548	99510	Amaguaña	Sandstone-breccia	Lithic sandstone-breccia. Clasts of sedimentary (red sandstone) and igneous origin (fine-grained K-feldspar rich trachytic? intrusives)
RH-232	7535	99515	Amaguaña	Siltstone	Poorly sorted lithics siltstone. Lithics of sedimentary rock types (siltstone), but some with very fine-grained (possibly K-feldspar rich)
RH-233	7530	99514	Amaguaña	Diorite	Altered fine grained diorite? with zoned plagioclase and chloritised mafics
RH-237	7489	99509	Manuel C. Astorga	Breccia	Breccia, containing igneous lithoclasts. These contain plagioclase and amphiboles in very fine-grained matrix
RH-238	7488	99511	Manuel C. Astorga	Breccia	Breccia with clasts of plagioclase and pyroxene phyric andesite in crystal-rich matrix
RH-239A	7462	99536	Tandapi	Sandstone	Tuffaceous sandstone with zoned euhedral plagioclase, very little K-feldspar, euhedral pyroxenes, in fine grained matrix of quartz and plagioclase
RH-239B	7462	99536	Tandapi	Andesite	Andesite with abundant plagioclase, commonly zones, euhedral pyroxene, some quartz
RH-241A & B	7462	99538	Tandapi	Breccia	Breccias with clasts of plagioclase phyric, pyroxene andesite, in fine grained, reddened, sedimentary matrix
RH-241C	7462	99538	Tandapi	Andesitic tuff	Andesitic tuff with abundant plagioclase and pyroxene in fine-grained sedimentary matrix
RH-241D	7462	99538	Tandapi	Andesite	Altered andesite, with plagioclase and pyroxene phenocrysts
RH-242	7443	99555	Tandapi	Granodiorite	Porphyritic granodiorite with zone plagioclase and biotite phenocrysts and some biotite
RH-246	7381	99619	Tandapi	Quartz-diorite	Quartz-diorite with amphibole and chlorite
RH-248A	7373	99633	Alluriquín	Breccia	Tuffaceous breccias, rich in plagioclase, quartz and igneous lithoclasts
RH-248B	7373	99633	Alluriquín	Breccia	Andesitic, tuffaceous breccia. Fine-grained, K-feldspar rich lithoclasts, some pyroxene, abundant quartz. Fine-grained sandstone lithics
RH-250B	7338	99633	Alluriquín	Sandstone	Poorly sorted sandstone, quartz and plagioclase-rich, no lithics. Matrix very fine-grained, almost entirely of quartz
RH-251A	7068	99426	Sta. María del Toachi	Breccia	Poorly sorted lithic breccia. Clasts of vesicular, fine-grained andesite, with euhedral pyroxenes
RH-253	7338	99780	Alluriquín	Sandstone	Poorly sorted coarse-grained sandstone, abundant quartz, plagioclase, and pyroxene, rare amphibole. Vesicular lithoclasts with K-feldspar
RH-254	7334	99786	Alluriquín	Breccia	Igneous lithoclasts within breccia of highly vesicular basaltic andesite, with plagioclase, pyroxene. Abundant amygdules of chlorite
RH-256	7270	99798	Pilaló	Sandstone	Fine-grained, laminated, quartz-rich sandstone. Fabrics are crenulations of a bedding plane fabric, with refraction along clay rich laminae

Sample	UTMX	UTMY	Topographic sheet	Rock type	Description
RH-258	7096	99432	Sta. María del Toachi	Sandstone	Well-sorted sandstone with abundant quartz, plagioclase and some pyroxene. One clasts of vesicular, very fine-grained igneous material
RH-259	7273	98955	Pilaló	Sandstone/Breccia	Volcanoclastic sandstone/breccia containing flattened vesicular lithoclasts
RH-260	7274	98954	Pilaló	Sandstone	Highly altered, very poorly sorted sandstone, with rare K-feldspar, and rare igneous lithoclasts containing K-feldspar
RH-261	7275	98953	Pilaló	Sandstone	Poorly sorted sandstone with reddened lithic, clasts of fine-grained igneous material. Rare clasts contain chlorite-filled vesicles
RH-265A	7165	99027	La Maná	Sandstone	Poorly sorted, crystal-lithic sandstone. Abundant clasts of highly vesicular, fine-grained andesitic material
RH-265B	7165	99027	La Maná	Sandstone	Fine-grained, quartz-lithic sandstone, with fine-grained lithics of feldspar-phyric andesite, vesicular in parts
RH-266	7246	99952	Pilaló	Breccia	Polymictic breccia containing mainly igneous clasts, including common reddened, fine-grained intrusives with K-feldspar laths
RH-267A	7258	99956	Pilaló	Sandstone	Carbonate-cemented sandstone, with quartz, little plagioclase, chloritised ferromagnesians, and abundant grains of reddened, opaque material
RH-267B	7258	99956	Pilaló	Breccia	Unsorted, polymictic breccias with mainly fine-grained igneous clasts of very fine-grained opaque material
RH-270	7203	99973	La Maná	Granodiorite	Coarse-grained, quartz, plagioclase, hornblende and biotite-bearing granodiorite. Very rare pyroxene
RH-271A	7168	99227	Pucayacu	Granodiorite	Coarse-grained, quartz, plagioclase and biotite-bearing granodiorite
RH-271B	7168	99227	Pucayacu	Granodiorite	Coarse-grained plagioclase, biotite, amphibole and quartz bearing granodiorite
RH-272	7118	99251	Pucayacu	Sandstone	Poorly sorted, lithic-rich sandstone. Lithics mainly of fine-grained basaltic-andesite composition
RH-273A	7084	99238	Pucayacu	Breccia	Breccia containing exclusively igneous lithoclasts, including weakly vesicular basaltic/andesitic material
RH-276	7200	99658	Santo Domingo	Basaltic andesite	Fine-grained, vesicular basaltic andesite. Chlorite and epidote fills to some vesicles, with much secondary calcite
RH-277	7207	99657	Santo Domingo	Sandstone	Poorly sorted, crystal-lithic sandstone. Crystal of plagioclase and pyroxene, lithics of very fine-grained, vesicular basalt/andesite
RH-278A	7249	99654	Alluriquín	Andesite	Fine-grained, plagioclase-rich, andesite, with rare olivine. Weakly vesicular in parts
RH-279A	7261	99655	Alluriquín	Basalt/Andesite	Fine-grained, plagioclase-rich basalt/andesite, with rare olivine? Weakly vesicular in parts
RH-280A	7277	99653	Alluriquín	Andesite/Basalt	Fine-grained andesite/basalt, with abundant epidote
RH-280D	7277	99653	Alluriquín	Sandstone	Crystal-rich sandstone, with plagioclase, quartz, common pyroxene and some epidote
RH-280F & D	7277	99653	Alluriquín	Basalt	Glassy pillow basalts (from pillow breccias), with chlorite and epidote infills. Shards present in matrix
RH-281A	7279	99654	Alluriquín	Sandstone	Coarse-grained, crystal-rich sandstone, with abundant altered plagioclase and quartz
RH-281B	7279	99654	Alluriquín	Sandstone	Fine-grained, well-sorted, quartz sandstone. No mafics, but some plagioclase
RH-282A	7219	99650	Santo Domingo	Basalt	Fine-grained, highly vesicular, epidotised basalt, with rare pyroxenes, and abundant, fine-grained plagioclase
RH-283A	7281	99655	Alluriquín	Sandstone	Altered, crystal-lithic, coarse-grained, poorly sorted sandstone. Lithic clasts of vesicular, fine-grained igneous material
RH-283B & C	7281	99655	Alluriquín	Sandstone	Crystal lithic sandstone, with clasts of vesicular, plagioclase-phyric, fine-grained, basic-intermediate igneous material
RH-286B & D	7272	99382	Jatunloma	Breccia	Epidotised and chloritised, poorly sorted lithic breccias. Lithics are of fine-grained vesicular basalt/andesite
RH-288	7333	99282	Jatunloma	Andesite	Very highly altered, pyroxene-phyric, vesicular andesite
RH-289	7336	99288	Jatunloma	Granodiorite	Altered, plagioclase-phyric, amphibole-phyric granodiorite, with some biotite
RH-290	7322	99295	Jatunloma	Sandstone	Poorly sorted, coarse-grained sandstone
RH-292	7309	99319	Jatunloma	Sandstone	Poorly sorted, coarse-grained, crystal lithic sandstone, rich in quartz and plagioclase. Lithics of fine-grained, commonly vesicular andesite
RH-293	7307	99319	Jatunloma	Andesite	Quartz and plagioclase-phyric, altered, fine-grained andesite
RH-294	7307	99321	Manuel C. Astorga	Sandstone	Well-sorted, quartz and plagioclase-rich, mafic-poor medium- to coarse-grained sandstone
RH-295	7310	99349	Jatunloma	Sandstone	Poorly sorted, coarse-grained, lithic sandstone. Clasts almost exclusively igneous, with rare, fine-grained sandstone
RH-296	7317	99425	Jatunloma	Basalt/Andesite	Fine-grained, weakly vesicular, weakly epidotised basalt/andesite
RH-297	7313	99439	Jatunloma	Basalt/Andesite	Fine-grained, weakly vesicular, weakly epidotised basalt/andesite

Sample	UTMX	UTMY	Topographic sheet	Rock type	Description
RH-302	7239	99309	Sigchos	Sandstone	Fine- to medium-grained, lithic sandstone, with clasts of very fine-grained, igneous material of basic to intermediate composition
RH-308	7195	99445	Sigchos	Sandstone	Fine-grained, well-sorted, quartz sandstone
RH-309	7555	99985	Latacunga	Peridotite	Serpentinised peridotite
RH-309C	7555	99985	Latacunga	Ultrabasic	Serpentinised ultrabasic with garnet?
RH-310	7557	99006	Latacunga	Sandstone	Quartz sandstone, with plagioclase, rare muscovite and lithoclasts of fine-grained quartz sandstone and small foliated clasts
RH-312	7567	99051	Latacunga	Siltstone/Mudstone	Extremely fine-grained, bioturbated siltstone/mudstone
RH-313	7551	99038	Latacunga	Sandstone	Moderately well-sorted quartz sandstone, with rare biotite and foliated grains. Rare aggregates of metamorphic? quartz
RH-313B	7551	99038	Latacunga	Sandstone	Well-sorted, fine to medium, quartz sandstone with some plagioclase and metamorphic grains. Pumpellyite very common in matrix
RH-314B	7560	99071	Latacunga	Sandstone	Well-sorted quartz sandstone with biotite and muscovite, in carbonate-rich matrix
RH-318	7247	99311	Jatunloma	Granodiorite	Granodiorite with phenocrysts of zoned plagioclase and rare biotite in very fine-grained matrix of quartz and plagioclase
RH-320A	7184	99234	Pucayacu	Granodiorite	Granodiorite with hornblende, plagioclase, quartz and biotite
RH-320B	7184	99234	Pucayacu	Granodiorite	Coarse-grained granodiorite, with plagioclase, quartz and biotite
RH-321	7452	99926	Mindo	Andesite	Altered, plagioclase-rich andesite?
RH-322	7464	99950	Mindo	Sandstone	Very poorly sorted crystal-lithic sandstone, with abundant rounded quartz and altered igneous material
RH-323	7428	99978	Mindo	Sandstone	Poorly sorted, crystal-lithic, sandstone, pyroxene-rich. Lithics are fine-grained, basic to intermediate, with rare pyroxenes and rarely vesicular
RH-324B	7434	99965	Mindo	Sandstone	Highly altered, lithic sandstone. Lithics are all basic igneous, pyroxene-rich and vesicular
RH-325B	7890	99261	Mindo	Sandstone	Sheared sandstone, with chlorite-filed strain-shadows and S-C fabrics throughout. Pumpellyite-grade. Quartz-rich, with mudstone lithics
RH-327	7296	99877	Mindo	Meta-sandstone	Foliated fine-grained metasandstone. Quartz and hornblende abundant, plagioclase rare
RH-328	7270	99925	Mindo	Siltstone	Laminated siltstone with quartz grains. Weakly developed S-C fabrics
RH-331A & B	7363	99965	Mindo	Sandstone	Pyroxene-rich, lithic, lithic sandstone, with basic to intermediate igneous lithoclasts, commonly vesicular, containing abundant pyroxene
RH-333	7279	99956	Mindo	Sandstone	Fine-grained sandstone with very weak cleavage. Quartz and plagioclase predominate, with no lithics or mafics
RH-337A	7689	99800	Alluriquín	Sandstone	Altered, fine-grained, quartz-lithic sandstone. Epidotised and chloritised
RH-337B	7689	99800	Alluriquín	Sandstone	Altered, epidotised, crystal-rich sandstone, with plagioclase, quartz and amphibole
RH-338B	7292	99799	Alluriquín	Sandstone	Altered, weakly epidotised, weakly sheared, poorly sorted sandstone. Plagioclase, quartz and amphibole rich, with igneous lithoclasts
RH-340A	7257	99818	Mindo	Sandstone	Poorly sorted, crystal-lithic sandstone. Amphibole common, pyroxene less common, lithoclasts include vesicular, plagioclase-phyric andesite?
RH-340B	7257	99818	Mindo	Sandstone	Coarse-grained, crystal lithic sandstone. Plagioclase common, pyroxene and altered amphibole present, with rare biotite. Fine-grained igneous lithoclasts
RH-341A	7224	99882	Cristóbal Colón	Siltstone	Crystal-lithic siltstone with euhedral pyroxenes, amphiboles and rare biotite. Lithoclasts of fine-grained, feldspar-phyric, basic igneous material
RH-341C	7224	99882	Cristóbal Colón	Sandstone	Crystal lithic sandstone with large zoned pyroxenes, some amphibole, and amphibole bearing, vesicular andesite lithoclasts
RH-343	7196	99169	Pucayacu	Granodiorite	Granodiorite with hornblende, biotite, quartz and plagioclase
RH-345	7090	99044	La Maná	Sandstone/Siltstone	Calcareous sandstone/fine-grained siltstone
RH-352B & C	7282	99656	Alluriquín	Sandstone	Poorly sorted, crystal-lithic sandstone, plagioclase and pyroxene rich. Lithoclasts of fine-grained sandstone and vesicular igneous material
RH-353A	7278	99656	Alluriquín	Sandstone	Coarse-grained, crystal-rich sandstone, with abundant altered plagioclase and quartz

APPENDIX 5 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA

OF ECUADOR

BETWEEN 0°00’ AND 1°00’ S

MAGNETIC SUSCEPTIBILITY

GEOLOGICAL INFORMATION MAPPING PROGRAMME

(LOCATION OF MAP 4 AREA)

QUITO, 1997

Magnetic susceptibility data

Magnetic susceptibility measurements were collected using a Kappameter instrument. The main objective of this exercise was to ascertain whether the main sedimentary units, and in particular the turbidite units, are distinguishable in the field. For this reason, data are available for the Yunguilla, Silante, and Saquisilí units, and for the Apagua Formation.

Sandstones of the Silante Unit are readily distinguishable because of their relatively high susceptibilities. Values from Saquisilí Unit sandstones in the type area are substantially higher than those in the type area of the Yunguilla Unit and the Apagua Formation, but the latter two units have indistinguishable values.

1. Yunguilla Unit

Values from the type area range from 0.06 (n = 12) and 0.12 (n = 6) in siltstone-dominated parts of the sequence, to 0.24 (n = 11) in sandier parts.

2. Silante Unit

Readings taken at two localities within sandstones in the sequence east of the Rio Chisinche in the type area gave mean values of 17.04 (n = 7) and 2.49 (n = 11). West of the Rio Chisinche at [7478-99517], coarse-grained sandstones of typical Silante composition gave a mean value of 3.30 (n = 11).

The magnetite bands exposed along the Quito-Chiriboga road at [7553-99697] are interpreted as possible placer beds. One band gave a value of 231, while four readings from the overlying sandstone sequence gave a mean of 28.13.

Two sets of readings from sandstones along the Nono-Tandayapa road have mean values of 5.62 (n = 12) and 16.85 (n = 9). Magnetite-rich placer bands at one of these localities gave single readings of 47.7 and 167.0. A set of readings from a quarry west of Tandayapa in Silante sandstones gave a mean of 34.12 (n = 4). Two sets of readings from Silante sandstones along the Calacalí-Nanegalito road gave mean values of 19.58 (n = 9) and 9.28 (n = 10).

3. Saquisilí Unit

Fine- to medium-grained sandstones in Quebrada Macas give a mean value of 0.40 (n = 39), fine- to medium-grained sandstones in Quebrada Pusuchusi give a mean of 0.30 (n = 36), and fine-grained sandstones in Quebrada Quila give a mean of 0.33 (n = 39).

4. Apagua Formation

Mean values of 0.06 (n = 10), 0.15 (n = 3) were obtained from siltstone-dominated parts and 0.25 (n = 9) from sandstone-dominated parts of the Formation.